EXPLORING MEDICINAL PLANTS

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Wild Edibles of Deserts

Food Security and Sustainability

Salman Majeed, Muhammad Zafar, Mushtaq Ahmad, Mohd Kafeel Ahmad Ansari, Shazia Sultana, and Andrea Pieroni

Wild Edibles of Deserts

Wild Edibles of Deserts: Food Security and Sustainability provides coverage of topics in food and health in desert rangelands, using an interdisciplinary approach that considers health not only in a functional and human sense but also in terms of external factors, including aridity.

The plant diversity in desert ecosystems provides economic service benefits, such as sources of fodder, fuel wood, and traditional medicinal plants. This book documents wild edibles commonly grown in deserts that are hugely beneficial for the herbal industry for the socio-economic uplift of local communities. This text contains multiple field pictorial graphs of desert wild edible plants to help with their identification, and it gives detailed information on food security issues and sustainability measures in the world desert zones. It also focuses on the diversity of wild edibles in deserts across the globe, their nutraceutical importance, production-consumption trends, integration into food menus, and marketing and livelihood opportunities for indigenous people.

A volume in the Exploring Medicinal Plants series, this book creates opportunity for policymakers to develop plans for the successful entry of wild edibles into herbal industries and attract farmers owning infertile lands to cultivate wild edibles in desert rangeland. The book is a valuable resource for researchers, conservationists, and policymakers seeking solutions at the intersection of food security and environmental sustainability.

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Prologue

This book explores the vital role of wild edible plants in desert ecosystems, offering insights into their potential for food security and sustainability. In arid environments, where traditional agriculture faces challenges, these resilient plants provide essential nutrition and resources. Through this work, readers will gain practical knowledge on identifying, harvesting, and utilizing wild edibles, while also understanding their ecological importance. *Wild Edibles of Deserts: Food Security and Sustainability* provides an in-depth exploration of the resilient plant species thriving in arid environments and their potential to enhance food security. This volume highlights the nutritional value and sustainable harvesting practices of desert-adapted plants, offering practical insights for communities facing food shortage. It emphasizes the importance of traditional ecological knowledge and modern research in promoting sustainable harvesting methods.

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Dr. Mohd Kafeel Ahmad Ansari
Prof. Shazia Sultana
Prof. Andrea Pieroni

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Preface

This book examines the importance of desert plants as a key resource for food security in arid regions. Deserts, often seen as barren landscapes, are home to a surprising variety of edible species that have supported indigenous peoples and wildlife for centuries. A volume in the Exploring Medicinal Plants series, this book provides detailed information on how these wild plants can be identified, harvested, and used for food, medicine, and other practical purposes. In an era of climate change and growing global food insecurity, desert wild edibles offer a sustainable solution for communities facing resource scarcity. The focus is on ecological principles, nutritional value, and sustainable harvesting techniques to ensure long-term viability. We can enhance food systems and promote environmental stewardship, making this knowledge vital for future generations in desert and semi-arid regions worldwide.

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About the Authors

Dr. Salman Majeed, a young scientist in the field of plant sciences, is an as assistant professor in the Department of Botany, University of Mianwali, Punjab Pakistan, particularly known for his expertise on plant biodiversity and taxonomic studies of deserts. He has published 50 research articles in various journals of good repute in impact factor journals, Google Scholar Citation (citations ±621, H-index 18, i10-index 26), and diverse fields of plant sciences. He has authored two international books and five international book chapters published by Elsevier, Springer, and Taylor & Francis/CRC Press. Dr. Majeed has participated in a number of conferences held at the national and international levels. His fields of interest are wild plant biodiversity of desert areas, plant taxonomy, food chemistry, nutraceuticals, palynology anatomy, melissopalynology, and medicinal plants ethnobotany.

Dr. Muhammad Zafar earned his PhD in plant sciences from Quaid-i-Azam University Islamabad, Pakistan in 2011. Currently, he is working as an associate professor (tenured), and Incharge Herbarium (ISL) in the Department of Plant Sciences, Quaid-i-Azam University, Islamabad, Pakistan. He is a renowned scientist in the field of medicinal plants, plant biodiversity, and plant systematics and biodiversity. He is the founder of the first melissopalynology and traditional medicinal plants labs, biofuel lab, and digital herbarium at Quaid-i-Azam University. Dr. Zafar has over 350 impact factor publications, ISI Web Sciences (citations ±8000, H-index 45), and Google Scholar Citations (citations ±15130, H-index 61, i10-index 315) in diverse fields of plant sciences. In addition, he is the author of 13 international books and 23 book chapters published by Elsevier, Springer, Taylor & Francis, Wiley, and more. He is the editorial board member of various journals of repute. He has successfully supervised/produced 18 PhD and 72 MPhil research scholars in advanced areas of plant systematics and biodiversity. He received productive scientist awards by PCST (2009–2017); TTS Awards of Performance-based Increment (2016–2020); a best research paper award by HEC (2011); a Gold Medal (Prof. Dr. Zabta Khan Shinwari Award) from Pakistan Academy of Sciences (PAS) in the field of biotechnology in 2021; and a Gold Medal award by Pakistan Academy of Sciences (2011) in the field of botany.

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He has been a visiting scientist at the University of South Australia, Adelaide, Australia in the Anadolu University, Turkey and at the Jamia Millia Islamia (Central University), New Delhi, India. He was associated with SP University, India as an associate professor of botany. Also, he served as the Australian Endeavour Awards Ambassador for higher educational institutions of India.

Prof. Ansari has more than 15 years of teaching and research experience in plant eco-physiology, plant stress physiology, industrial and environmental biotechnology, environmental microbiology, microbial genetics, microbiology, molecular biology, aromatics and medicinal plants, plant-microbe-soil interactions and phytoremediation technology as well as cyanobacterial. He has published over 40 research papers in peer-reviewed international journals, edited three books as a main editor with Taylor & Francis, US, authored 20 book chapters, co-authored many book chapters, and is currently editing three books with international publishers, including Elsevier, Springer Nature, Taylor & Francis/CRC Press, and more. Prof. Ansari has successfully supervised two PhDs, ten MSc, and ten BS research scholars in multidisciplinary research areas including cyanobacterial biotechnology, medicinal botany, microbiology, and plant sciences at national and international levels. He has received several grants for his international research projects. He served as a member of the Departmental Research Committee, Academic Council, Board of Research Studies, Faculty Board, Faculty Representative and Advisory Board for Graduate Studies and Research at various universities of the world.

He's been involved with several professional memberships of India, Dubai, Italy, Germany, Hong Kong, Japan, Spain, and the US. He attended various national and international conferences and invited talks. Due to his diverse expertise in interdisciplinary research, Prof. Ansari is in high demand as an external PhD thesis examiner worldwide. He also figured in various scientific committees globally and placed in the AD Scientific index. At present, he is serving as a member of many editorial boards and a reviewer of a number of high impact international scientific journals. He has been involved with international and multidisciplinary research projects globally.

Dr. Shazia Sultana is a young scientist in the field of plant biology and biodiversity and non-timber forest products, with 300 research publications (to date) in top international journals, more than 11543 citations (660 impact factor, H-index 57 & I-index 215), and 12 international books published internationally. Dr. Sultana is an awardee of various national and international awards. She was selected by the Institute of Post Graduate studies, USM Malaysia, Higher Education Commission, and Pakistan Council for Science and Technology. She is also an editorial board member of many well-reputed ISI journals and book series.

Prof. Dr. Andrea Pieroni was trained in medical botany at the University of Pisa, Italy. Prof. Pieroni earned his doctorate from the University of Bonn in Germany. He has been a research assistant at the University of London (2000–2003), a tenured lecturer, and a senior lecturer at the University of Bradford in northern England (2003–2009). In 2009, he was hired as a professor of ethnobotany at the University of Pollenzo, Italy of which he has been the vice chancellor from 2017–2021.

Prof. Pieroni has served as vice president and president of the International Society of Ethnobiology (2008–2010), founder and chief editor of the *Journal of Ethnobiology and Ethnomedicine*, and sits on the boards of diverse international peer-reviewed journals. His main research focus is on temporal and diachronic changes of local plant knowledge among minorities, diasporas, cultural, and geographical boundaries in the Mediterranean, the Balkans, Eastern Europe, and the Middle East. According to a 2022 Stanford University study, he was among the top 1% of the most quoted worldwide scientists.

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List of Abbreviations

^{13}C NMR	Carbon-13 Nuclear Magnetic Resonance
^{1}H NMR	Proton Nuclear Magnetic Resonance
2,4-D	2,4-Dichlorophenoxyacetic acid
α-amylase	Alpha-amylase
α-glucosidase	Alpha-glucosidase
µg/mg	Micrograms per milligram
ACA	Arid Central Asia
AHSs	Agricultural Heritage Systems
AJ	*Acacia jacquemontii*
AJEAE	*Acacia jacquemontii* ethyl acetate extract
AJHE	*Acacia jacquemontii* n-hexane extract
Akt	Protein kinase B
AMPK	AMP-activated protein kinase
BAP	6-Benzylaminopurine
BCa	Breast cancer cells
Ca	Calcium
CAM	Crassulacean Acid Metabolism
CCD	Convention to Combat Desertification
CCl_4	Carbon Tetrachloride
CE	Catechin Equivalent
CE	Common era
CO_2	Carbon dioxide
COVID-19	Coronavirus disease 2019
Cr	Chromium
CS	*Capparis spinosa*
Cu	Copper
DBP	Diastolic blood pressure
DCI	Dominance Candidate Index
DCM	Dichloromethane
DPPH	2,2-Diphenyl-1-picrylhydrazyl
DPP-IV	Dipeptidyl Peptidase IV
DW	Dry weight
EAC	Ehrlich ascites carcinoma
EtOAc	Ethyl acetate
FAO	Food and agriculture organization
FD	Flowering desert
Fe	Iron
G	Growth
GAE	Gallic acid equivalent
GC-MS	Gas chromatography-mass spectrometry
GG	Guar gum
GHG	Greenhouse gas
GM	Gura meal
HDL	High-density lipoprotein
HeLa	Henrietta lacks
HEPa	Hexane: Ethyl acetate
HepG2	Human hepatocellular carcinoma cell line

HPLC	High-performance liquid chromatography
HPTLC	High-performance thin-layer chromatography
HYA	Hyaluronidase
IC_{50}	Inhibitory concentration 50%
JNK	c-Jun N-terminal kinase
K	Potassium
LC-MS	Liquid chromatography-mass spectrometry
LDH	Lactic dehydrogenase
LDL	Low-density lipoprotein
LEK	Local ecological knowledge
L-NAME	N(G)-nitro-L-arginine methyl ester
LOX	Lipoxygenase
M	Mitosis
MAB	Man and biosphere
MAP	Mean arterial pressure
MCF7	Michigan Cancer Foundation-7
MG63	MG63 osteosarcoma
MICs	Minimum inhibitory concentrations
Mn	Manganese
MS medium	Murashige and Skoog medium
NMR	Nuclear magnetic resonance
NPs	Nanoparticles
NRs	Natural resources
OD	*Opuntia dillenii*
ODSO	*Opuntia dillenii* Seed Oil
ORAC	Oxygen radical absorbance capacity
P53	Tumor protein 53
PC3	Prostate cancer 3
pH	Potential of hydrogen
PI	Propidium iodide
PTEN	Phosphatase and tensin homolog
PTP1B	Protein tyrosine phosphatase 1B
PUFA	Polyunsaturated fatty acid
QE	Quercetin equivalent
RSM	Response surface methodology
SBP	Systolic blood pressure
SDGs	Sustainable development goals
SK-MES-1	Squamous cell carcinoma mesothelioma-1
STZ	Streptozotocin
T47D	T47D breast ductal carcinoma
TCM	Traditional Chinese medicine
TEAC	Trolox equivalent antioxidant capacity
TEK	Traditional ecological knowledge
TLC	Thin layer chromatography
UAE	United Arab Emirates
UNCOD	United Nations Conference on Desertification
UNESCO	United Nations Educational, Scientific and Cultural Organization
UN	United Nations
USA	United States of America
UV	Ultraviolet
Vitamin B1	Thiamine

Vitamin B2	Riboflavin
Vitamin C	Ascorbic acid
WE	Wild edible
WEs	Wild edibles
WEPs	Wild edible plants
WFPs	Wild food plants
WHO	World Health Organization
ZJ	*Ziziphus jujuba*
ZJB	*Ziziphus jujuba* bark
ZJC	*Ziziphus jujuba* core
ZJF	*Ziziphus jujuba* fruit
ZJL	*Ziziphus jujuba* leaves
ZJR	*Ziziphus jujuba* roots
Zn	Zinc

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Introduction

This book prime focus is to cover topics on the diversity of wild edibles (WEs) in deserts across the globe, their nutraceutical importance, production-consumption trends, integration into the current food menu, and marketing and livelihood opportunities to indigenous people. The purpose of this book is to provide coverage of emerging topics in food and health in desert rangelands, using an interdisciplinary approach that considers health not only in a functional and human sense but also in terms of external factors such as aridity. Desert plant activity is limited first and foremost by low water availability, but more specifically it is the pulsed nature of water availability and periods of severe water limitation between these pulses that have most strongly impacted the ecology of desert biota. Climate variability, geographic isolation, geologic history, and edaphic anomalies are among the primary drivers for greater-than-expected plant biodiversity.

The plant diversity in this ecosystem provides economic service benefits, such as sources of fodder, fuel wood, and traditional medicinal plants. The book documents WEs commonly grown in deserts, and a compiled catalog of wild edibles in the desert, which is very helpful for research communities of allied disciplines and the herbal industry for the socio-economic uplift of local communities. Unlike other wild edible food books on desert rangeland, this book contains multiple field pictorial graphs of desert wild edible plants on a worldwide scale to help with identification. This book also gives detailed tips on food security issues and sustainability measures in the world desert zones. The prime focus is to cover topics on the diversity of WEs in deserts across the globe, their nutraceutical importance, production-consumption trends, integration into the current food menu, and marketing and livelihood opportunities to the indigenous people.

The major goals of this book are confined to establishing plant-based industries for academic research at an institutional level, and providing opportunities for policymakers to develop plans for the successful entry of wild edibles into herbal industries. This book is helpful in addressing food shortage and can motivate farmers owning unfertile lands to cultivate wild edibles in desert rangeland. Indigenous knowledge regarding the value of WE diversity plays a significant role in the development of nutraceutical products to accelerate innovations for food security and enhance the sustainable utilization of WEs.

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1 Introduction

1.1 WHY ARE DESERTS TRENDY?

Deserts have surged in popularity due to their exotic allure, minimalist beauty, and promise of adventure (Figure 1.1). Their vast landscapes, characterized by sweeping dunes, rugged rock formations, and clear skies, captivate the imagination and attract those seeking unique experiences (Kishore et al., 2024). The rise of desert-inspired design trends and minimalist aesthetics reflects a growing appreciation for their simplicity and natural elegance. Moreover, deserts offer opportunities for wellness retreats, environmental consciousness, and cultural exploration, drawing individuals seeking tranquility, sustainability, and spiritual connection. As awareness of their ecological importance grows, deserts have become not only trendy destinations but also symbols of conservation and mindful living in an increasingly fast-paced world (Ponte, 2012).

Deserts have emerged as a popular subject for exploration in the realm of global wild edibles due to their unique ecological characteristics and the potential they have for enhancing food security and sustainability (Cooke & Warren, 2023). Despite their harsh environments, deserts are home to a surprising diversity of edible plants that have adapted to thrive in extreme conditions, offering valuable resources for resilient food systems. By delving into the culinary traditions and nutritional value of desert wild edibles, this book aims to uncover untapped sources of sustenance while promoting the conservation of desert ecosystems and indigenous knowledge. Through the lens of desert wild edibles, readers can gain insights into innovative approaches to food production, resilience-building, and sustainable living in an era of climate change and environmental uncertainty (Deller et al., 2020).

FIGURE 1.1 Expansive view of sand dunes shaped by wind erosion.

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Desert rangelands, similar to other arid regions, face significant challenges stemming from natural disturbances, including extensive soil degradation and sparse rainfall patterns, largely influenced by their geographical positioning within climatically harsh environments (Chawicha & Tussie, 2023). These challenges are further exacerbated by human activities such as overgrazing and excessive wood harvesting. Collectively, these factors lead to diminished biodiversity, reduced rangeland productivity, and heightened erosion rates, presenting widespread and persistent issues across desert ecosystems (Gamoun et al., 2018).

Deserts represent a distinct and vital ecosystem spread across our planet, running parallel to the equator at latitudes of 25–35° in both the Northern and Southern Hemispheres. Climatically, the desert biome encompasses all arid and hyper-arid regions globally, while biologically, it encompasses the habitats of plants and animals specially adapted to thrive in arid conditions (Middleton, 2009). Characterized by minimal rainfall (< 400 mm), extreme aridity, and sparse vegetation, deserts may seem devoid of life at first glance. However, they host a remarkable and diverse array of species and biological communities with significant conservation importance (Roy & Roy, 2019).

Arid rangelands stand as vital ecosystems, offering a multitude of services and serving as habitats for pastoral and agro-pastoral communities. Encompassing a range of habitats and ecological communities, these lands hold significant economic value due to their abundance of edible plants, forage, medicinal resources, and economically valuable species (Rasmussen et al., 2012). Disturbances within arid rangelands have notably pronounced and far-reaching impacts on plant biodiversity, surpassing those observed in other ecosystems. Numerous studies have demonstrated the adverse effects of grazing, drought, and human interventions on the biodiversity and plant species diversity within these environments (Gamoun & Louhaichi, 2021).

The popularity of deserts in the context of global wild edibles is significant as it reflects a growing interest in alternative food sources that can contribute to food security and sustainability. Exploring the culinary potential of desert wild edibles not only highlights the resilience of these ecosystems but also offers insights into traditional knowledge systems and indigenous food practices (Mariutti et al., 2021). By shedding light on the nutritional value, culinary uses, and conservation of desert plants, this book aims to elevate the importance of desert wild edibles in addressing global food challenges. Understanding and harnessing the potential of these often-overlooked resources can enhance food sovereignty, promote biodiversity conservation, and foster sustainable livelihoods, making a meaningful contribution to the quest for a more resilient and equitable food system (Nabhan et al., 2022).

Deserts offer a plethora of services and goods crucial for human well-being and survival, ranging from water provision to medicinal resources and raw materials, catering to the needs of both local inhabitants and neighboring communities. Despite their vital role, comprehensive information about the benefits derived from this biome remains fragmented (Bublitz et al., 2019). Consequently, deserts have often been neglected in ecosystem valuation studies. Notably, the Middle East serves as a significant region where numerous plant and animal domestications originated, with many wild relatives of domesticated species still thriving in desert locales, underscoring the biome importance in biodiversity conservation and its potential for providing essential resources (Bidak et al., 2015).

The current trend of aridification is a global concern, posing threats to ecosystems and economies across regions. The increasing dryness of landscapes worldwide is a result of various factors such as shifts in atmospheric circulation patterns, solar radiation levels, and wind patterns, which collectively influence regional climate conditions. These elements play a crucial role in shaping geomorphic landscape processes, determining the availability of groundwater resources, and impacting environmental sustainability (Chlachula, 2021).

The agricultural technologies employed by desert communities entail advanced methods for harvesting and managing water, which have facilitated their flourishing. This study identifies thousands of macro-botanical remains (charred wood) and micro-botanical remains (fossilized pollen), offering direct evidence for the first time of the fruit trees that were integral to the success of this distinctive desert horticultural venture (Langgut et al., 2021).

Deserts have long served as historical trade routes, facilitating the exchange of goods and cultures over millennia. Their warm climates also enable the export of agricultural products, cultivated through irrigation, to regions beyond the desert. Already proven profitable in places like Israel and Tunisia, agriculture and horticulture hold significant promise in regions like Thar (Vaks et al., 2006). Aquaculture presents a novel non-traditional export from deserts, benefiting from potentially more efficient water usage compared to desert plants. Moreover, mild winter temperatures and low land costs in deserts support this endeavor (Farrag et al., 2021). Deserts' abundant solar radiation year-round fosters the production of valuable biologically derived chemicals, including those from micro-algae and medicinal plants, which are exported to global markets. Despite the ongoing export of wild plant products from deserts, there remains untapped pharmaceutical potential in desert flora (Roy & Roy, 2019).

The concept of desert cultivation has gained global attention as a means to address food shortages and prevent malnutrition. Significant efforts have been made to cultivate strategic crops and maximize productivity per unit area. However, overlooking environmental considerations and overexploitation of natural resources (NRs) has led to degraded soil and declining productivity. While industrial fertilizers have been used as a solution, they are not sustainable in the long term (Grainger, 2013). Consequently, there is an urgent global need to implement environmentally sustainable practices in desert agriculture to mitigate these losses. Despite the extreme conditions of deserts, they harbor diverse flora and fauna communities. These organisms have developed specific adaptation features to survive in such harsh environments. The phenomenon of adaptation occurs through prolonged exposure to slow and repetitive stimuli, allowing species to acclimate and endure challenging conditions (Ahmad et al., 2022).

Deserts are attracting attention due to their potential for sustainable agriculture, climate change aquaculture, and renewable energy projects, facilitated by advancements in technology and a growing global awareness of environmental issues (Figure 1.2).

However, the unique biodiversity and cultural significance of deserts contribute to their appeal as destinations for ecotourism and botanical exploration (Table 1.1).

1.2 EXTENT OF CLIMATE ARIDITY IN DESERTS

Deserts play a crucial role in the Earth's landscape and exert significant influence on global climate dynamics through feedback mechanisms. The extent of climate aridity in deserts is characterized by extremely low levels of precipitation, typically less than 250 millimeters annually, coupled with high evaporation rates. This combination results in arid conditions where water availability is severely limited, leading to sparse vegetation cover and minimal soil moisture (Cooke & Warren, 2023). Deserts often experience wide temperature variations, with scorching daytime heat and chilly nights due to limited cloud cover and insulation. These climatic factors contribute to the harsh and inhospitable conditions that define desert environments, shaping the unique ecosystems and biodiversity found within them (Eckardt et al., 2022).

Amidst ongoing global climate change trends, semi-arid and desert fringe ecosystems are encountering diminishing water reserves and escalating atmospheric temperatures (Shoshany & Mozhaeva, 2023). However, our comprehension of the climatic factors influencing the spatial and temporal variability of deserts worldwide remains limited. Deserts, characterized by extremely dry climates, typically feature bare surfaces, minimal vegetation, low precipitation, and high evaporation rates. Desert regions expand or contract due to global climate change. Alterations in regional ecosystems occur, impacting human communities and livelihoods. Changes in desert

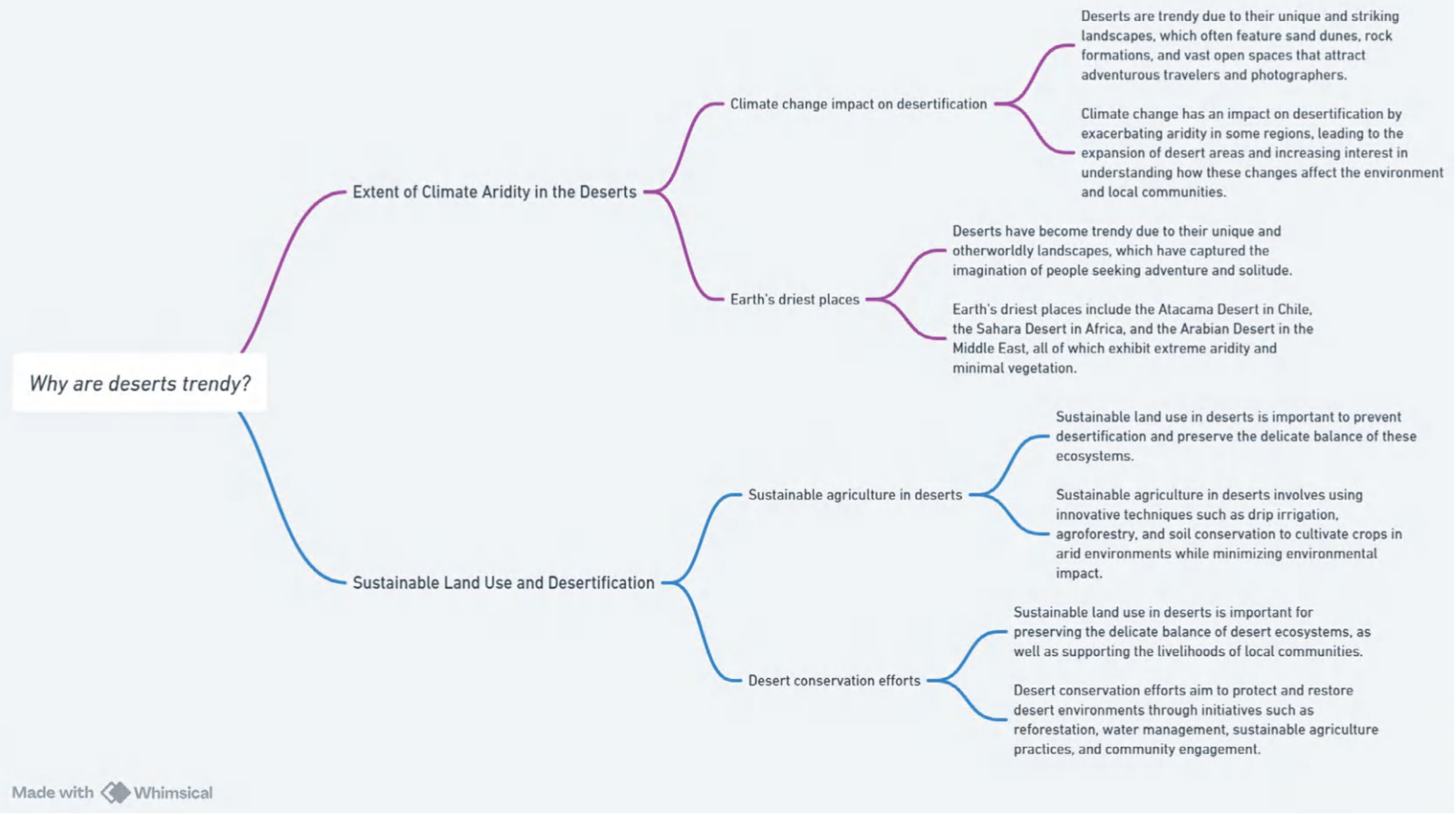

FIGURE 1.2 Overview of desert trends and the challenges of agricultural sustainability linked to climate change.

TABLE 1.1
Overview of Unique Aspects of Desert Areas

Sr. No.	Aspects	Explanation	Reference
1.	Unique landscapes	Deserts boast unique and diverse landscapes, including sand dunes, rock formations, and vast open spaces	Zavala-Hurtado and Jiménez (2020)
2.	Adventure appeal	The allure of adventure and exploration draws people to deserts for activities such as hiking, camping, and dune bashing	Rose (2023)
3.	Photography	Desert landscapes offer stunning photo opportunities, with dramatic lighting, textures, and natural beauty	Barromi-Perlman (2020)
4.	Spiritual retreats	Many deserts are associated with spiritual and meditative practices, offering solitude and introspection	Mayes (2023)
5.	Cultural significance	Deserts are often steeped in cultural history and folklore, attracting visitors interested in indigenous cultures and traditions	Fanood (2014)
6.	Environmental awareness	Increased awareness of environmental issues has led to interest in desert ecosystems and conservation efforts	Shali (2008)
7.	Eco-tourism	Sustainable tourism initiatives in deserts promote eco-friendly practices and education about desert conservation	Khaleghian and Sharghi (2023)

surface characteristics also influence local climate and atmospheric circulation patterns through interactions between land and the atmosphere. Studying variations in desert extent is essential for enhancing our understanding of landscape change processes and underlying driving forces, offering valuable insights for desertification prevention and control initiatives (Chen et al., 2023).

Drylands encompass over 35% of the Earth land area, and their global coverage is expanding due to projected increases in aridity driven by climate change. As ecosystems become more arid due to climate change, deserts emerge as some of the most challenging environments to inhabit (Dong et al., 2024). Arid lands are integral components of Earth human and physical environments, playing a crucial role in global biophysical processes by regulating solar radiation and atmospheric constituents. Water scarcity is a defining characteristic of these regions, with hyper-arid, arid, and semi-arid areas experiencing persistent water scarcity, frequent droughts, and high climatic variability. Covering 41% of the Earth's land surface, these regions support approximately 2.5 billion people who rely directly on arid land ecosystems for their livelihoods, hosting 50% of the world livestock and contributing to 44% of global food production. Classified into four categories based on the aridity index – hyper-arid, arid, semi-arid, and dry sub-humid – these regions face threats to livelihood sustainability from complex social, economic, and environmental changes, presenting significant challenges to researchers, policymakers, and rural land users alike (Gaur & Squires, 2018). The geological formations of desert plateaus demonstrate how prolonged climate aridity has shaped their structure through processes such as erosion and sedimentation (Figure 1.3).

Earlier studies examining variations and long-term trends in aridity lack the necessary detail for effective planning of ecological restoration projects due to their limited spatial and temporal resolutions. Precipitation, air temperature, and aridity patterns across extensive regions fluctuate both spatially and temporally due to diverse climatic conditions influenced by geographic location,

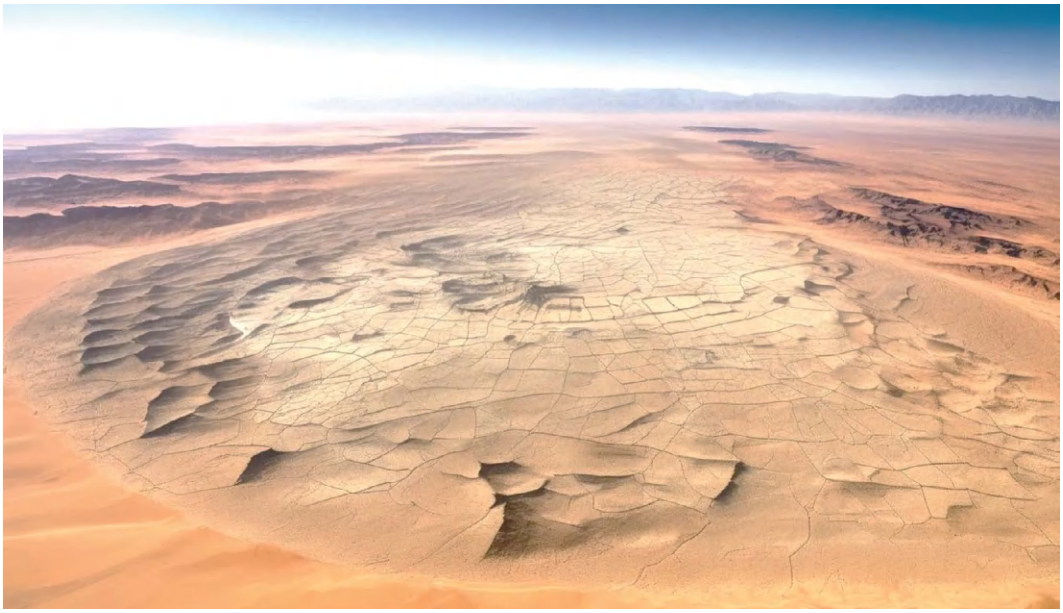

FIGURE 1.3 Desert plateau illustrating geological formations influenced by climate aridity.

large-scale weather systems, terrain features, prevailing wind patterns, proximity to moisture sources, and other factors. Against the backdrop of climate change, it remains uncertain how spatial differences in associated eco-hydrometeorological variables affect the development of ecological restoration projects (Shao et al., 2018; Yang et al., 2013).

The impact of climate change on biodiversity is increasingly evident, prompting conservation efforts to prioritize understanding species' responses to these changes. Identifying a species vulnerability to climate change involves considering biological traits related to sensitivity and adaptive capacities. Desert-dwelling species, in particular, may face heightened vulnerability due to potentially living near their physiological thresholds (Araújo & Pérez, 2023). Deserts and arid regions host a surprisingly rich variety of species, largely shaped by robust climatic influences. Through convergent evolution of biological traits and adaptive processes, desert species display distinctive morphological, physiological, or behavioral adaptations to extreme climates. Moreover, in arid environments, fluctuations in precipitation can have particularly pronounced effects on biodiversity compared to other ecosystems. Alterations in precipitation patterns directly impact species by influencing germination rates and the availability of food and water resources (Bachelet et al., 2016; Vale & Brito, 2015).

Desert expansion and contraction, influenced by both climate and human activities, are integral to the ongoing debate surrounding desertification in dryland regions. A comprehensive assessment of the Gobi Desert in East Asia, using high-resolution satellite data and a meteorologically derived aridity index spanning from 2000 to 2012, revealed a recent reduction in its size. This fluctuation in desert area, predominantly driven by precipitation patterns, contradicts numerous reports suggesting human-induced desertification in Mongolia and China. The concerns regarding alterations in the peripheries of the Sahara Desert and the looming threat of desertification led to the examination of desert boundaries. Tucker et al. (1991) were among the first to introduce remote sensing as a method for quantifying vegetation biomass, paving the way for further research in this area. Changes in vegetation driven by precipitation are indicative of the prevailing climate patterns impacting East Asia. In the central and southern regions of the Gobi Desert, fluctuations in monsoonal climate significantly influence vegetation biomass, while the northern part is notably

FIGURE 1.4 Panoramic landscape showcasing sparse vegetation in arid conditions.

influenced by the Siberian-Mongolian high-pressure system, resulting in cold and arid climatic conditions (Sternberg et al., 2015).

Perennial grass biomass, along with other forms of photosynthetic primary production, serves as a vital ecosystem service in these regions, facing threats from various global changes. The escalating aridity linked to climate change is particularly alarming as it jeopardizes multiple aspects of ecosystem dynamics, including the sustained quantity and quality of primary productivity. The intensification of aridity exacerbates water scarcity, diminishes continuous vegetative cover, reduces the availability of forage for livestock and wildlife, and accelerates the encroachment of invasive woody plant species (Havstad et al., 2018). Declines in primary productivity also carry significant implications for environmental health and human well-being, including socioeconomic dependency on livestock production. In this context, understanding how temporal shifts in aridity impact the composition and biomass of plant communities is crucial for mitigating the consequences of climate change (Lasché et al., 2023). Figure 1.4 depicts the sparse vegetation typical of arid environments adaptations of plant species survival in low-water conditions.

In order to achieve the Sustainable Development Goals (SDGs) related to good health and well-being (SDG 3), clean water and sanitation (SDG 6), zero hunger (SDG 2), sustainable cities and communities (SDG 11), responsible consumption and production (SDG 12), and climate action (SDG 13), a circular economy model prioritizing the efficient utilization of water resources is essential. The scarcity of fresh water in desert regions presents a significant obstacle to food production. Integrating advanced nutrient recovery systems such as anaerobic digestion into their food production processes can help close the loops for both water and nutrients (Cabrera-González et al., 2022).

The United Nations (UN) Decade for Deserts and the Fight against Desertification concluded in 2020. Despite the common association between deserts and desertification, it is crucial to distinguish between the two. Deserts represent mature ecosystems characterized by extremely low productivity, primarily due to severe water limitations resulting from minimal rainfall and high evapotranspiration rates. These ecosystems have evolved under such conditions over extended periods. On the other hand, desertification entails the degradation of land, diminishing

its capacity to support life and provide essential ecosystem services to human populations. This process often results in the displacement of communities. According to the UN Convention to Combat Desertification (UNCCD), desertification is defined as land degradation in arid, semi-arid, and dry sub-humid areas caused by various factors, including climatic variations and human activities (Martínez-Valderrama et al., 2020).

The alteration of plant cover has far-reaching implications for the global carbon cycle, contributing to warming and climate changes. Vegetation plays a crucial role in heat transfer and the release of water vapor, which in turn influences rainfall patterns. According to Gray and Brady (2016), plants are currently facing individual climate change factors, but this will evolve in the future as they confront multiple environmental stressors simultaneously. Many studies investigating plant responses to climate change focus on exposing plants to single factors at a time, which is experimentally manageable but limits the ability to draw conclusions about how plants will react to realistic climate change scenarios. The impact of climate warming on desert plants remains poorly understood. While there is a prevailing notion that desert vegetation will expand in response to climate change, the specific plant species that will withstand anticipated temperature increases remain uncertain (Al-Blooshi et al., 2020).

Despite the numerous and severe environmental challenges present in deserts, plants, animals, and microbes have evolved adaptation mechanisms enabling their growth, survival, and reproduction under such extreme conditions. Ancient civilizations inhabiting these deserts utilized plants for various purposes such as food, clothing, shelter, fuel, and medicinal treatments. In modern times, plants play a crucial role in providing economically, medically, and industrially valuable resources to humans. Due to the harsh environmental conditions of desert habitats, plant growth is limited, predominantly consisting of shrubs and grasses. Desert flora primarily comprises short-lived annual plants, succulent perennial plants (stem or leaf succulents) adapted to conserve moisture, and non-succulent perennials including shrubs, herbs, grasses, and trees (Alsharif et al., 2020).

The influence of climate stability on the endemism of wild edible food vascular plants in desert regions is profound. Desert ecosystems are characterized by extreme environmental conditions, including limited water availability and high temperatures, which exert selective pressures on plant species. Climate stability plays a crucial role in shaping the distribution and abundance of these plants, as it affects their ability to adapt and persist in such harsh environments (Medeiros & Drezner, 2012). In regions with more stable climates, endemic species of wild edible plants are more likely to evolve and thrive, as they can specialize in order to exploit unique ecological niches and develop adaptations to withstand the prevailing climatic conditions. Conversely, areas experiencing greater climatic variability may witness lower levels of endemism, as species face challenges in adapting to rapidly changing environmental conditions. Understanding the relationship between climate stability and the endemism of wild edible plants is essential for conservation efforts and sustainable management of desert ecosystems, as it provides valuable insights into the resilience and vulnerability of these species in the face of ongoing climate change (Sosa et al., 2020).

The semi-arid and arid agro-climatic zones host a plethora of plants, many of which thrive as wild and overlooked denizens of the desert terrain, bearing edible fruits. These plants demonstrate resilience in extreme temperatures, marginal lands, and water-scarce conditions, offering sustainable food sources for the future. Their contributions to ecosystems and communities are multifaceted: (1) influencing agricultural productivity in agroforestry systems, such as enhancing yields for crops like cereals; (2) serving as balanced functional foods, rich in high-quality protein, macro- and micro-nutrients, and addressing protein-calorie malnutrition; and (3) acting as sources of anti-oxidants, nutraceuticals, and bioactive compounds to combat the rising burden of non-communicable diseases such as obesity, diabetes, and cardiovascular disorders (Joshi et al., 2023).

Several promising desert plants include *Prosopis cineraria, Acacia senegal, Cyamopsis tetragonoloba*, *Capparis decidua, Ziziphus mauritiana* (jujube), *Cordia dichotoma, Leptadenia pyrotechnica, Calligonum polygonoides,* and various millets. While the potential of these plants has been acknowledged by food and agricultural scientists, there are research gaps such as low

yield, susceptibility to diseases, presence of anti-nutrients, lack of genomic sequence information, exclusion from formal food value chains, and inadequate marketing strategies, hindering the realization of their full potential (Subbulakshmi et al., 2023).

This current perspective explores the promise offered by underutilized plants from desert regions in ensuring food and nutrition security, along with the potential to develop value-added agri-food products from them. Moreover, it emphasizes the complementary role of food processing technologies in achieving these goals, aiming to transform desert plants from traditional sources to climate-smart future foods.

1.3 SUSTAINABLE LAND USE AND DESERTIFICATION

Desertification, a type of land degradation primarily observed in semi-arid and arid regions, stems from a combination of climatic shifts and human activities (Figure 1.5). It affects approximately 25% of the Earth drylands, home to over a third of the global population. Economic losses due to desertification have amounted to around US $42.3 billion globally (Shu et al., 2023). This phenomenon is influenced by changes in temperature, rainfall, and wind patterns, which can either exacerbate or mitigate its impact. Human actions that disrupt the delicate balance of arid and semi-arid ecosystems, coupled with natural climatic variations, contribute significantly to the spread of desert-like conditions in non-desert areas. Addressing desertification is crucial for fostering sustainable development, as it poses a significant challenge to environmental stability (Lyu et al., 2020). The promotion of wild edible food sustainability plays a crucial role in mitigating the impacts of land degradation. By incorporating wild edible plants into land management practices, communities can enhance biodiversity, improve soil health, and provide alternative food sources, thereby contributing to ecosystem resilience and food security in arid and semi-arid regions affected by desertification (Smith et al., 2020).

1.3.1 Desertification: Causes and Impacts

Desertification has been characterized as the transformation of forested areas into savannas. Imeson (2012), defines it as the significant deterioration of land, resembling desert conditions due to human overuse and climate variations. The United Nations Conference on Desertification (UNCOD) in Nairobi in 1977 defined desertification as the depletion or destruction of a land's biological capacity, potentially resulting in desert-like conditions due to a combination of adverse climate conditions and excessive exploitation. The conventional perception of desertification

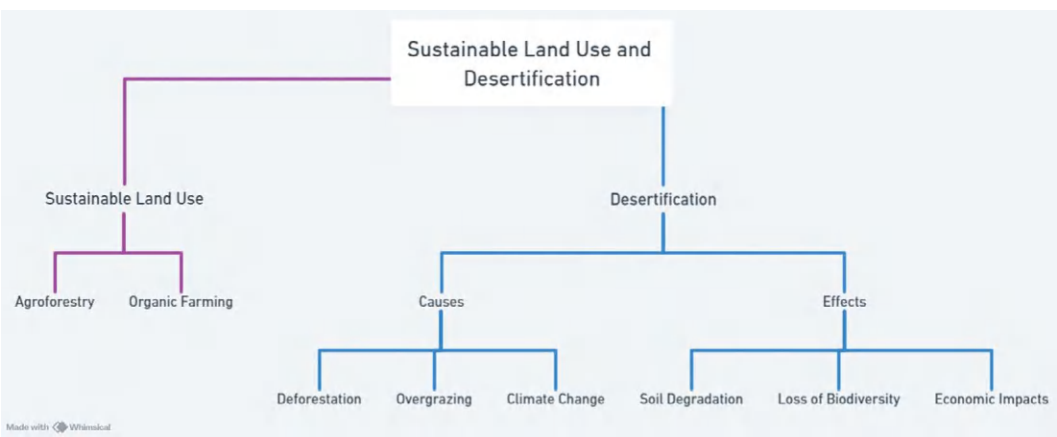

FIGURE 1.5 A flowchart of sustainable land management and desertification threats.

FIGURE 1.6 Panoramic view illustrating the varying patches of desert soil areas affected by desertification and their impact on ecosystems.

often portrays sand dunes encroaching upon agricultural fields and encircling the fringes of deserts. However, this depiction is oversimplified, as desertification encompasses a complex array of processes (Figure 1.6). In essence, desertification arises from distinct processes that act independently or in concert within dryland regions, leading to environmental degradation (Nwilo et al., 2020).

Desertification stands as a significant environmental challenge confronting humanity, as it diminishes ecosystem services, exacerbates food insecurity and poverty, and impacts societal well-being. Understanding this process is highly intricate due to its occurrence across various temporal and spatial scales, influenced by diverse factors. It is widely acknowledged that land use and land cover change emerge as primary catalysts for desertification, as environmental degradation consistently stems from the depletion of natural vegetation cover (Vieira et al., 2021).

Various studies have reflected the direct impact of human activities and climatic factors on exacerbating land degradation and desertification (Cowie et al., 2011). Desertification can thus be characterized as the deterioration of land productivity and the emergence of landscapes prone to aridity, attributed to human intervention in natural systems and changes in climatic conditions (Geist & Lambin, 2004). Climate change significantly influences desertification by altering regional water availability, soil moisture, and vegetation cover (Tucker et al., 1991). Dynamic desert boundaries are heavily influenced by annual rainfall, with reductions in precipitation leading to vegetation declines. Furthermore, desertification contributes to social and political instability in drylands through adverse effects such as dust storms, flash flooding, and changes in terrestrial carbon and nitrogen pools (Sagdic, 2022).

Transformative change in land management and food production sectors is addressed to tackle the global challenges of climate change mitigation, adaptation, combating land degradation and desertification, and ensuring food security (Smith et al., 2020). Desertification is universally recognized to have significant adverse effects on affected populations and countries. It results in accelerated soil erosion by wind or water, accumulation of salt in soils, decreased species diversity and plant biomass, and diminished overall productivity of dryland ecosystems. This process often leads to the conversion of usable drylands into land unsuitable for agriculture or settlement. The loss of soil fertility represents a major socio-economic consequence of desertification, directly impacting

yields, food production, and people's incomes. Consequently, this exacerbates poverty, drives migration or displacement, and contributes to social breakdown, potentially leading to political instability (Patel et al., 2021).

1.3.2 Importance of Sustainable Land Use

Land degradation represents a significant challenge to the sustainability of food security, livelihoods, ecosystem services, and biodiversity conservation. The global arable land area is estimated to be 7616 million acres, comprising only 24% of the total land surface, with approximately half of this area currently under cultivation. The productivity of arable land primarily hinges on soil formation and its effective management. Soil comprises mineral components, organic matter, and microorganisms in a natural, dynamic equilibrium that has evolved over thousands and millions of years (geologic ages). Human pressures and unsustainable land use practices disrupt this balance, leading to soil degradation within a relatively short timeframe. Thus, there is a pressing need for a global initiative to raise awareness about the economic ramifications of land degradation and to advocate for sustainable land management practices. This initiative should focus on conducting a comprehensive global study to assess the economic benefits derived from land and terrestrial ecosystems. Developing countries face heightened vulnerability to desertification and land degradation due to limited infrastructure and financial resources, which hinder their ability to implement sustainable land management practices (AbdelRahman, 2023).

The common drivers of desertification in dryland regions are attributed to climate change and unsustainable land management practices. Arid and semi-arid ecosystems naturally experience low or erratic rainfall, and prolonged droughts can swiftly diminish ecosystem productivity, transforming fertile areas into desert-like landscapes devoid of moisture. For farmers, sustaining livelihoods becomes exceedingly challenging in regions with less than three inches of annual rainfall (Ruiz et al., 2020). Unfortunately, this scenario is not fictional. Deserts are expanding at a rate of approximately 20,000 square miles per year. This rapid expansion presents a widespread and urgent issue affecting millions worldwide. Shockingly, an estimated 2 billion people bear the brunt of desertification consequences globally. Desertification significantly contributes to hunger in many parts of the world, as it diminishes available land for agriculture and animal husbandry. Consequently, food shortages become increasingly prevalent in affected regions (Ronda-Borzone et al., 2022).

Combating desertification effectively necessitates a combination of preventative and remedial measures. Enhancing the resilience of both the environment and communities in affected areas involves implementing sustainable land management practices, initiating reforestation and afforestation projects, and adopting efficient water conservation and management strategies. Moreover, mitigating the impacts of desertification and promoting the sustainable utilization of NRs can be achieved through the restoration of degraded land and vegetation cover utilizing soil and vegetation restoration techniques (Ayub et al., 2020). To preserve the environment and ensure social stability, it is imperative to prevent desertification. Tree planting can play a crucial role in rehabilitating degraded land and improving soil quality. Afforestation, the establishment of forests in previously barren areas, can mitigate the effects of desertification by reducing erosion and enhancing soil fertility. Sustainable land management practices such as agroforestry, sustainable grazing, and conservation agriculture not only improve soil quality and reduce erosion but also enhance biodiversity. These practices can also contribute to increased agricultural productivity and the creation of new income-generating opportunities for local communities (Pal et al., 2023).

1.3.3 Strategies for Combating Desertification

The UNCCD spearheads international initiatives aimed at addressing desertification, advocating for participatory approaches. These efforts prioritize dialogue among diverse perspectives, often rooted in individual interests rather than societal welfare, leading to sluggish progress in

implementation. Addressing desertification and land degradation is crucial for preserving food security, alleviating poverty, and mitigating the negative effects of climate change and biodiversity loss. Numerous strategies have been developed to tackle desertification and land degradation (Kong et al., 2021). Combatting desertification necessitates collaborative endeavors, encompassing the adoption of innovative practices, biotechnological solutions, restoration of oases, ongoing reforestation efforts, and rehabilitation of agricultural lands (Sarparast et al., 2020). In recent years, several countries and international organizations have initiated endeavors to combat desertification and alleviate drought impacts in different global regions. By 2018, an agreement involving 197 countries was signed to implement measures aimed at combating desertification (Al-Obaidi et al., 2022).

Over the years, governments have enhanced their scientific and technological capacities in desertification control through advancements in basic scientific research and applied technology (Lackey, 2007). While financial resources and investment in science and technology are crucial for combating desertification, policies, and regulations play a vital role in providing guidance and direction. Despite the introduction of desertification control policies and regulations by countries and regions participating in the Belt and Road Initiative (BRI; a global infrastructure and economic development strategy launched by China in 2013 to enhance connectivity and cooperation across Asia, Europe, and Africa), there is a deficiency in regional cooperation and international exchange (You et al., 2021). Risk assessment aids in identifying regional and local strategies to combat desertification, which may involve alterations in agricultural and land-use policies, as well as soil conservation measures. Furthermore, it provides land managers with tools for long-term planning. Desertification risk assessment facilitates the creation of maps depicting risk potential and intensity, as well as hazard maps, to enhance future management efforts. The outcomes of desertification risk assessment encompass management of land cover and water resources, optimal resource utilization, and preservation of ecosystem integrity (Akbari et al., 2021).

1.3.4 Case Studies in Successful Desertification Mitigation

The various studies showcasing successful desertification mitigation efforts exemplify the efficacy of holistic approaches such as afforestation, sustainable land management practices, and community involvement. These initiatives demonstrate the potential to restore degraded landscapes and mitigate the impacts of desertification through concerted and innovative efforts.

THE LOESS PLATEAU, CHINA

The Loess Plateau suffered severe soil erosion and desertification due to unsustainable agricultural practices and deforestation. However, China government implemented the "Grain for Green" program, which involved afforestation, terracing, and soil conservation measures. This initiative has successfully restored vegetation cover, reduced soil erosion, and improved water retention, thereby mitigating desertification (Yu et al., 2020).

THE NEGEV DESERT, ISRAEL

Israel has employed innovative techniques such as drip irrigation, water recycling, and agroforestry to combat desertification in the Negev Desert. These practices have enabled sustainable agriculture, increased vegetation cover, and minimized soil degradation, transforming arid landscapes into productive agricultural areas (Prince & Safriel, 2021).

THE GREAT GREEN WALL, AFRICA

The Great Green Wall initiative aims to combat desertification across the Sahel region of Africa by planting a belt of trees and vegetation to prevent soil erosion and promote biodiversity. Countries like Senegal have successfully implemented this project, leading to increased vegetation cover, restoration of degraded land, and improved livelihoods for local communities (Sileshi et al., 2023).

REWETTING PEATLANDS IN INDONESIA

Indonesia has undertaken efforts to rewet degraded peatlands, which were drained for agriculture, to mitigate desertification and reduce carbon emissions. By restoring water levels and promoting the growth of peat-forming vegetation, such as mangroves and peat swamp forests, Indonesia has successfully halted soil degradation and restored ecosystem functions in these areas (Mizuno et al., 2023).

SUSTAINABLE LAND MANAGEMENT IN NIGER

Niger has implemented sustainable land management practices such as farmer-managed natural regeneration (FMNR) and agroforestry to combat desertification and improve food security. These initiatives have led to increased vegetation cover, enhanced soil fertility, and diversified livelihoods for rural communities, contributing to the mitigation of desertification (Sadda et al., 2023).

1.3.5 Policy Frameworks and International Cooperation

Policy frameworks and international cooperation are integral components in addressing sustainable land use and desertification on a global scale. The UNCCD serves as a key policy framework, providing guidance and support for countries to implement strategies for combating desertification and promoting sustainable land management. Through the UNCCD, countries collaborate to develop action plans, share best practices, and mobilize financial resources to support projects aimed at addressing land degradation and desertification (Bristol-Alagbariya, 2023).

Furthermore, international cooperation plays a crucial role in fostering knowledge exchange and capacity building among nations facing similar challenges related to desertification and land degradation. Platforms such as the Global Environment Facility (GEF) provide funding and technical assistance to support projects aimed at sustainable land management and biodiversity conservation. Furthermore, regional cooperation initiatives, such as the African Union Great Green Wall, facilitate collaboration among multiple countries to implement large-scale landscape restoration projects aimed at combating desertification and improving livelihoods for local communities. By promoting policy alignment, knowledge sharing, and resource mobilization, international cooperation enhances the effectiveness of efforts to address sustainable land use and desertification at both national and global levels (Batra et al., 2022; do Nascimento, 2023).

1.4 CONCLUSION AND IMPLICATIONS

Deserts have gained popularity due to their unique landscapes and the allure of adventure associated with exploring these arid regions. However, it's important to recognize that the extent of climate aridity in deserts presents significant challenges, particularly in terms of sustainable land use and combating desertification. In the context of arid desert food security, the harsh environmental

conditions pose obstacles to traditional agriculture. Yet, deserts hold potential for sustainable food production through innovative approaches such as agroforestry, hydroponics, and drought-resistant crop cultivation. Moreover, the cultivation and promotion of wild edible plants indigenous to desert ecosystems can contribute to food security by diversifying diets and providing alternative sources of nutrition.

Addressing sustainable land use and desertification in arid regions requires a multifaceted approach. It involves implementing conservation measures to protect fragile desert ecosystems, promoting sustainable land management practices to prevent soil degradation, and enhancing water resource management to mitigate the impacts of climate aridity. Furthermore, investing in research and development is crucial to better understand the ecological dynamics of desert environments and to identify strategies for enhancing food security while preserving biodiversity. Looking ahead, the future needs in arid desert regions involve continued collaboration between governments, international organizations, and local communities to develop comprehensive strategies for sustainable land use and desertification mitigation. This includes investing in education and capacity building, fostering community engagement in NR management, and leveraging technology and innovation to overcome the challenges posed by climate aridity. By prioritizing these efforts, we can work towards ensuring food security, preserving biodiversity, and promoting sustainable development in arid desert regions.

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2 Brief Overview of Deserts of the World

Ecology, Climate, Flora, Population

Deserts are present on every continent and encompass approximately one fifth of the Earth's land area, with about one sixth of the global population living in them. These deserts vary in type, such as polar and tundra, cold winter, mild coastal, and subtropical (Varghese, 2023). Four primary categories of deserts are recognized: (1) subtropical deserts, (2) cool coastal deserts, (3) cold winter deserts, and (4) polar deserts. The majority of arid deserts are situated near the equator, benefiting from ample sunlight. Vegetation types correlate closely with the availability of water in each habitat. Due to the diversity in landforms, soils, fauna, flora, water dynamics, and human influences, there is no singular definition that encapsulates arid environments comprehensively. However, the defining characteristic of all arid regions is their aridity (Abd El-Ghani et al., 2017). The desert ecosystem plays a prominent global role, with features such as windbreaks and sand stabilization, soil conservation, nitrogen fixation, oxygen production, regulation of water resources, biodiversity preservation, support for tourism, and cultural significance (Wang et al., 2022).

Despite increasing interest in deserts, there remains a need for a thorough biogeographical overview that encompasses key organisms, ecosystem characteristics, and processes unique to these environments. Such an overview could reveal the factors influencing their current distribution patterns. This is crucial for accurately predicting the future state of deserts and for devising more effective strategies for their restoration and conservation (Maestre et al., 2021). Deserts are characterized by low precipitation levels and extreme temperature variations, often resulting in sparse vegetation adapted to arid conditions. Their ecological dynamics are shaped by specialized flora and fauna capable of conserving water and thriving in harsh climates. Despite their challenging environment, deserts support diverse populations of adapted organisms and have significant ecological importance globally (Greenville et al., 2012).

This chapter provides a concise survey of deserts across different regions: South Asia, Central Asia, Arabia, Africa, Europe, and Latin America. Each section explores the unique ecological characteristics, climate patterns, flora, and population dynamics that define these diverse desert landscapes.

2.1 SOUTH ASIAN DESERTS

South Asian deserts encompass a variety of arid and semi-arid regions that play significant ecological and climatic roles in the subcontinent. These deserts primarily include the Thar Desert in India and Pakistan, known for its expansive sand dunes and sparse vegetation adapted to extreme heat and water scarcity. The region experiences high temperatures during the day and considerable temperature drops at night, characteristic of desert climates (Yadav & Lal, 2018). Flora in South Asian deserts consist of xerophytic plants such as cacti, thorny shrubs, and succulents that have evolved mechanisms to conserve water and withstand arid conditions (Reddy et al., 2019).

The population density in these deserts varies, with communities often relying on nomadic or semi-nomadic lifestyles centered around pastoralism and subsistence agriculture. Human settlements

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are typically clustered around oases or along river valleys where water resources are more accessible (Goodall, 2007). Despite the challenges posed by limited water availability, this region hosts a diverse array of wildlife adapted to desert life, including reptiles, small mammals, and avian species. It is crucial to consider the ecological dynamics and human interactions within South Asian deserts for conservation efforts and sustainable development practices aimed at preserving these unique and fragile ecosystems (Chlachula, 2021).

South Asia, despite being known for its lush landscapes and diverse climates, also contains several notable desert regions. Here are some of the prominent deserts found in South Asia: the Thar Desert (Great Indian Desert), the Cholistan Desert (also known as Rohi Desert), the Kutch Desert (Rann of Kutch), the Thal Desert, and cold deserts.

2.1.1 Thar Desert

The Thar Desert, spanning parts of Rajasthan in India and eastern Pakistan, is characterized by a fragile and unique ecosystem adapted to extreme arid conditions (Table 2.1; Figure 2.1). Its biodiversity is relatively low compared to more temperate regions, comprising primarily hardy species such as drought-resistant shrubs, thorny bushes, and ephemeral plants that bloom briefly after rainfall (Ravi & Huxman, 2009). Wildlife includes species like the Indian gazelle (Chinkara), desert fox, and various reptiles and birds. Human activities such as agriculture and grazing have impacted the desert ecology, leading to issues of desertification and habitat degradation (Ghalib et al., 2018).

The Thar Desert experiences a hyper-arid climate with scorching hot summers and cold winters. Summer temperatures often exceed 45°C (113°F) during the day, while winter nights can drop below freezing. Annual rainfall is low, averaging between 100 and 500 mm, and is highly variable from year to year. Water sources are scarce, mainly relying on groundwater reserves and occasional rainfall events which trigger brief periods of plant growth and wildlife activity (Chaudhry, 2017; Varghese, 2023). Water scarcity is widespread across many regions, restricting agricultural activities. Groundwater is typically found at depths ranging from 50 to 300 ft, with varying levels of salt concentration. Ponds, dugouts, and tanks filled during monsoon rainfall serve as the most accessible and immediate water sources. Over the past 50 years, plant biodiversity in the deserts of Sindh has been significantly depleted due to droughts, disasters, and irregular rainfall patterns exacerbated by global warming and rapid climate change. The vegetational patches in the Thar Desert reflect the stability and diversity of plant species that have adapted to the harsh, arid conditions of Thar desert's unique ecosystem (Figure 2.2).

The flora of the Thar Desert is adapted to survive with minimal water, characterized by species such as *Acacia*, *Prosopis cineraria* (Khejri), *Capparis decidua* (Karir), and various species of grasses and ephemerals (Roy & Roy, 2019). Many plants have developed mechanisms such as deep root systems, reduced leaf surface area, and waxy coatings to minimize water loss and endure harsh desert conditions. During favorable conditions, the desert can bloom with colorful flowers, though these periods are short-lived (Sharma, 2023).

Thar Desert is sparsely populated, with most communities concentrated near water sources or in oasis-like settlements known as "dhani" or "dera". The population consists primarily of indigenous desert dwellers known as Rajputs, along with pastoral communities such as Rabaris and Meghwals who traditionally engage in livestock herding and subsistence agriculture (Saha et al., 2000). Modern developments such as irrigation projects and tourism have brought changes to traditional lifestyles, impacting both the environment and socio-economic dynamics of the region (Hun, 2020).

TABLE 2.1
Key Geographical and Climatic Features of the Thar Desert

Sr. No.	Aspect	Details	Citation
1.	Location	Northwestern India and southeastern Pakistan	Dhir et al. (2018)
2.	Area	Approximately 200,000 square kilometers (77,000 sq mi)	Usman et al. (2024)
3.	Topography	Rolling sand dunes, rocky hills, salt flats (Rann of Kutch), and ephemeral streams	Dhir et al. (2018)
4.	Climate	Hot desert climate with extreme temperature variations *Summer*: up to 50°C (122°F) during the day, cooler nights *Winter*: as low as 0°C (32°F) at night, mild daytime temperatures	Dhir et al. (2018)
5.	Rainfall	Very low annual precipitation Average less than 250 mm (10 in) per year *Season*: mostly during monsoon (July to September), unreliable and highly variable	Choudhary (2021)
6.	Temperature extremes	*Maximum*: up to 50°C (122°F) in summer *Minimum*: near freezing point in winter nights	Bilal et al. (2017)
7.	Soil type	Sandy with some areas of saline soil Poor in nutrients	Usman et al. (2024)
8.	Flora	Adapted to arid conditions *Trees and shrubs*: *Acacia*, Neem, Khejri, Rohida, Babul *Thorny bushes*: cacti, euphorbia, caper *Grasses*: Sewan, Khus-khus, Ronjh, Chibber, Laana	Meena (2017)
9.	Fauna	Diverse despite harsh conditions *Mammals*: Indian gazelle (chinkara), Indian wild ass (khur), desert fox, desert cat, blackbuck *Birds*: bustards, sandgrouse, falcons, eagles, vultures	Meena (2017)
10.	Aquatic life	Sparse, limited to certain seasonal water bodies (dands)	Dhir et al. (2018)
11.	Human population	Sparse, primarily rural communities engaged in agriculture (irrigated farming where possible), animal husbandry, and tourism	Roy and Singhvi (2016)
12.	Human influence	Traditional water conservation techniques (e.g., step wells), modern interventions (irrigation projects), and sustainable tourism initiatives	Bilal et al. (2017)
13.	Challenges	Water scarcity, soil erosion, desertification, and loss of biodiversity	Garg and Choudhary (2021)
14.	Conservation efforts	Afforestation projects, wildlife sanctuaries (e.g., Desert National Park in India), sustainable agriculture practices, and community-based conservation initiatives	Usman et al. (2024)

2.1.2 Cholistan Desert

The Cholistan Desert, located in southeastern Pakistan, presents a distinct ecological profile characterized by its arid landscape, dominated by rolling sand dunes interspersed with rocky outcrops and saline depressions (Figure 2.3; Table 2.2). The desert topography supports a variety of flora and fauna adapted to extreme desert conditions (Zubair et al., 2018). Vegetation primarily consists of drought-resistant shrubs such as *P. cineraria* (khejri), *Acacia jacquemontii* (guggal), and *Calotropis procera* (Sodom apple), alongside hardy grasses like *Cenchrus ciliaris* (buffel grass) and *Cymbopogon jwarancusa* (jwar). Despite the harsh environment, the Cholistan Desert harbors a surprising diversity of wildlife, including endemic species like the chinkara (Indian gazelle), desert monitor lizard, and various avian species that have adapted to sparse and seasonal water sources (Abdullah et al., 2017).

FIGURE 2.1 The Thar Desert, showcasing its vast sandy landscapes and undulating dunes.

FIGURE 2.2 Vegetational patches in the Thar Desert, illustrating the diverse plant species adapted to arid conditions.

FIGURE 2.3 Landscape of the Cholistan Desert patches of *Tamarix* trees that thrive in the arid environment.

TABLE 2.2
Geographical Characteristics of the Cholistan Desert

Sr. No.	Aspect	Details	Citation
1.	Location	Southeastern Pakistan, extending into eastern Pakistan and western India	Altaf (2022)
2.	Area	Approximately 26,300 square kilometers (10,200 sq mi)	Altaf (2022)
3.	Topography	Rolling sand dunes, rocky outcrops, salt flats (locally known as "dhand"), and occasional small hills	Ahmad (2011)
4.	Sand dunes	Extensive areas of rolling sand dunes, some reaching heights of up to 150 m	Ahmad (2011)
5.	Rock formations	Rocky outcrops scattered throughout the desert, composed of sandstone and shale	Ahmad (2011)
6.	Salt flats (Dhands)	Large, flat areas covered with salt and clay deposits, often temporarily flooded during the monsoon season, supporting unique flora and fauna adaptations	Ahmad (2011)
7.	Ephemeral streams	Seasonal streams (locally called "tohis") that flow after rain, providing temporary relief to the arid landscape	Hameed et al. (2011)
8.	Vegetation	Sparse vegetation adapted to arid conditions, including drought-resistant shrubs and grasses	Hameed et al. (2011)
9.	Human settlements	Sparse, with traditional settlements and nomadic camps primarily near water sources and oases	Khan et al. (2004)
10.	Geological features	Fossil deposits, remnants of ancient riverbeds, and occasional fossilized marine life indicating past geological changes	Khan et al. (2004)

For centuries, the economy of the desert has relied predominantly on pastoral and nomadic practices, guided largely by the onset of the monsoon and the distribution of rainfall. The vegetation in the Cholistan desert consists of xerophytic species well-adapted to harsh conditions such as extreme temperatures, scarce moisture, and challenging soil conditions. The Cholistan desert is renowned for its unique biodiversity, geological formations, archaeological treasures, and historical sites that depict ancient cultures. It is also home to diverse ethnic groups with rich traditional knowledge and customs (Asif et al., 2023). However, these invaluable resources face increasing threats due to rising human populations, climate change, and the overexploitation of natural resources. Preserving and leveraging traditional knowledge related to biodiversity conservation and sustainable resource use is crucial for the continued existence of this historic desert ecosystem. Effectively implementing policies that promote conservation and sustainable natural resource management is essential for the long-term preservation of desert biodiversity (Wariss et al., 2021). The traditional habitational place in the Cholistan Desert reflects the significance of plant-based resources fundamental to local folklore community (Figure 2.4).

The climate of the Cholistan Desert is typical of a hot desert, characterized by extreme temperature fluctuations throughout the year. Summers are scorching hot, with daytime temperatures often exceeding 45°C (113°F), while winters are relatively mild during the day but can drop to near freezing at night. Rainfall is minimal and highly erratic, averaging less than 150 mm (6 in) annually, primarily during the monsoon season from July to September. The region aridity is exacerbated by strong winds that shape and maintain the desert's characteristic sand dunes and barren expanses (Hussain & Abbas, 2019; Wariss et al., 2021).

The flora of the Cholistan Desert has adapted to survive in arid and sandy conditions, comprising mainly xerophytic species that can withstand prolonged droughts and high temperatures. Common plant species include *A. jacquemontii* (Guggal), *P. cineraria* (Khejri), *Calligonum polygonoides*

FIGURE 2.4 Traditional dwelling site in the Cholistan Desert, emphasizing plant-based resources in local folklore.

(Kari), and *Salvadora persica* (Toothbrush tree). These plants typically have deep root systems to access groundwater and often feature thorny or waxy leaves that reduce water loss through transpiration. The desert also supports ephemeral vegetation like annual grasses and herbs that flourish briefly after sporadic rainfall events (Ejaz et al., 2023; Shahzad et al., 2022).

The human population of the Cholistan Desert is predominantly rural, with communities primarily engaged in pastoralism, agriculture, and handicrafts. Nomadic tribes in the Cholistan traditionally rear livestock, particularly camels, goats, and sheep, which are well-adapted to the harsh desert environment (Haider et al., 2021). Settlements are sparse and often centered around natural oases or water sources, where agriculture largely dependent on irrigation is practiced on a small scale. The desert population faces challenges related to water scarcity, limited access to healthcare and education, and few economic opportunities, although efforts are underway to improve living conditions and sustain traditional ways of life through community-led initiatives and government support (Malik & Ali, 2017).

2.1.3 Kutch Desert

Kutch Desert, located in Gujarat, India, specifically the Great Rann of Kutch, presents a distinctive ecosystem (Figure 2.5; Table 2.3). For most of the year, it exists as a hot, saline desert that undergoes regular flooding during the Indian monsoon season. During the dry season, extensive crystallized salt deposits create what is known as the "white desert" across large areas (Kerepesi & Grolmusz, 2016). Covering an expanse of 7,505 km^2, the Rann of Kutch stands as one of the world largest salt deserts. Its vast, parched landscape consists of dark silt coated with salt, which transforms into a stunning coastal wetland following seasonal rains. The Rann of Kutch serves as a significant ecotone, bridging marine and terrestrial ecosystems. This region endures harsh climatic extremes, with summer temperatures averaging around 44°C and peaking at 50°C, while winter temperatures can approach or dip below freezing (Pandit et al., 2015).

The Little Rann of Kutch is a salt marsh characterized by high salinity levels, reaching up to 12,094 parts per million (ppm). Unlike many other deserts, it predominantly comprises clay, which makes up 60% of its soil composition. This salt marsh supports a diverse plant ecosystem, including 253 flowering plant species, 23 shrubs, 18 climbers, 157 herbs, 18 tree species, and 33 types of grass. Dominant plant species in this region include *Suaeda* spp., *S. persica*, *C. decidua, C.*

FIGURE 2.5 Panoramic view of the Kutch Desert, represent its vast, arid, dry landscape.

TABLE 2.3
Peculiar Attributes of the Kutch Desert

Sr. No.	Aspect	Details	Citation
1.	Location	Western India, primarily in Gujarat State	Varghese (2023)
2.	Geography	Large arid to semi-arid region, characterized by salt marshes and desert	Biswas et al. (2022)
3.	Climate	Hot desert climate with low rainfall (less than 500 mm annually)	Tyagi (2023)
4.	Temperature	Extreme temperature variations Can reach up to 50°C in summer	Tyagi (2023)
5.	Soil type	Sandy and saline soils, with areas of alluvial deposits	Biswas et al. (2022)
6.	Vegetation	Sparse xerophytic vegetation, thorny shrubs, drought-resistant plants	Biswas and Chauhan (2021)
7.	Flora	*Acacia species, Prosopis juliflora, Salvadora persica, Capparis decidua*	Sadhu et al. (2022)
8.	Fauna	Asiatic wild ass (*Equus hemionus*), desert fox (*Vulpes vulpes pusilla*), Indian hedgehog (*Paraechinus micropus*), various reptiles and migratory birds	Singh (2024)
9.	Water sources	Few and sporadic natural water bodies Reliance on groundwater and reservoirs	Tyagi (2023)
10.	Human impact	Grazing, salt extraction, and agricultural activities affecting biodiversity	Rabari et al. (2023)
11.	Conservation status	Protected areas like the Wild Ass Sanctuary Efforts to conserve endemic species	Singh (2024)
12.	Challenges	Desertification, water scarcity, habitat fragmentation	Singh (2024)

procera, *Tamarix* spp., and *Aeluropus lagopoides* (Goswami et al., 2014). The Little Rann of Kutch has been proposed as a biosphere reserve, recognized internationally under the U.N.E.S.C.O. Man and Biosphere (M.A.B.) program, which encompasses terrestrial and coastal ecosystems of significant ecological importance (UNESCO World Heritage Centre). The phoenix tree plays a vital role in the sustainability of the Kutch Desert, providing shade and stabilizing the soil with its extensive root system. Its ability to withstand extreme aridity and high temperatures makes it a vital species for maintaining biodiversity in this harsh environment (Figure 2.6)

This sanctuary in the Little Rann of Kutch represents a unique ecological system characterized by a saline desert climate, exhibiting minimal floral diversity but rich faunal diversity. This sanctuary is specifically designated to protect the free-ranging population of the Indian Wild Ass. The area transforms into a seasonally flooded wetland ecosystem during the monsoon season. Salinity levels gradually vary during this period, with a noticeable gradient observed from seawater to river water (Koyani et al., 2009). Internationally recognized for its natural and geomorphological significance, the site holds high conservation value for research and eco-tourism. The transitional climatic conditions of the saline desert suggest potential adaptations of microorganisms to the challenging environmental factors, such as pH, salinity, and temperature variability (Patel et al., 2015).

The Little Rann of Kutch lies within the northern semiarid climatic zone and serves as a meeting point for various phytogeographic regions, exhibiting diverse floral elements. The region suffers extreme climatic variations: it gets inundated by tidal waters and freshwater from seasonal rivers during the monsoon, while in summer, water retreats and evaporates, leaving behind halite and gypsum crystal crusts forming in clay and sand (Bhatt & Singh, 2022). The distribution patterns of both biological elements and human activities in the area largely correlate with the prevailing bioclimatic conditions. Anthropogenic activities such as pastoralism, salt mining, and dry farming not only

FIGURE 2.6 *Phoenix* tree thriving among the shifting sands of the Kutch Desert, illustrating flexibility in harsh conditions.

reflect the climatic characteristics of the region but also influence its ecological dynamics (Gupta, 2015). The Kutch desert harbors numerous culturally significant plants, yet their conservation status remains poorly understood due to human activities, both direct and indirect. Despite the critical role of Kutch flora in the vegetation of Indian semiarid regions, there is a notable lack of studies focusing on essential aspects of plant conservation such as germination characteristics, reproductive biology, and autecology (Raole et al., 2010).

2.1.4 Thal Desert

The Thal Desert is situated in northeastern Pakistan, positioned between the Indus and Jhelum rivers near the Pothohar Plateau (Figures 2.7 and 2.8; Table 2.4). It spans approximately 190 miles in length from north to south, with a maximum width of 70 miles and a minimum of 20 miles. The climate is tropical, characterized by sporadic annual rainfall averaging around 250 mm. During summer, strong gusty winds frequently trigger sandstorms. Temperatures in the region can soar as high as 50°C during the hottest months. The floristic diversity of the Thal Desert encompasses a total of 38 families, 116 genera, and 248 species, as reported by Shaheen et al. (2014). The most prominent family, *Poaceae*, contributes 52 species to the desert flora, including economically significant grass species (Chaudhari et al., 2013). In terms of avian diversity, the desert hosts 55 species and 42 genera from 28 families. Key wildlife species in the area include the Punjab urial and

FIGURE 2.7 Thal Desert rangeland patterns of scarce vegetation across its vast land, reflecting aridity.

FIGURE 2.8 *Tamarix aphylla* vegetation growing at Mankera Fort, demonstrating adaptation to arid conditions.

TABLE 2.4
Key Environmental and Socioeconomic Features of the Thar Desert

Sr. No.	Parameters	Description	Citation
1.	Climate	Hot and arid Temperature extremes Low annual rainfall (< 200 mm/year) High evaporation rates	Garzanti et al. (2020)
2.	Soil characteristics	Sandy and loamy Low organic content Poor water retention Alkaline pH	Garzanti et al. (2020)
3.	Vegetation	Sparse xerophytic vegetation Drought-resistant plants such as *Acacia* spp., *Prosopis cineraria* (Khejri), *Capparis decidua* (Kair) Limited biodiversity	Yasin et al. (2024)
4.	Wildlife	Adapted to desert conditions Species include desert foxes, rodents, snakes, various bird species (larks, sandgrouse), insects (beetles, ants)	Fatima et al. (2019)
5.	Water resources	Limited natural surface water Dependence on underground aquifers (aquifer depth, recharge rates) Traditional water harvesting techniques	Raza et al. (2024)
6.	Land use patterns	Nomadic herding (camels, goats, sheep) Agriculture in irrigated patches Limited industrial development Some tourism potential	Munir et al. (2022)
7.	Livelihood	Primarily pastoralism and subsistence agriculture Reliance on livestock (milk, meat) and staple crops (wheat, millets) for food and income	Hamza et al. (2024)
8.	Food availability	Seasonal fluctuations in crop yields Dependence on imported food during lean periods Traditional food preservation methods (drying, pickling)	Abbas et al. (2020)
9.	Nutritional status	Variable dietary diversity Prevalence of malnutrition (especially among children and vulnerable groups) Micronutrient deficiencies	Khalid et al. (2021)
10.	Government interventions	Subsidized food programs Water management initiatives (desalination, rainwater harvesting) Agricultural subsidies Community-based conservation projects	Ahmed et al. (2023)

chinkara, with sightings of blackbucks in limited numbers. The region has also recorded sightings of four major species: the one-horned rhinoceros, Asiatic cheetah, wild ass, and tiger, alongside swamp deer and lions. Seventeen reptile species across 13 genera have also been reported (Khan et al., 2017).

The Thal Desert of Pakistan is situated at altitudes ranging approximately from 200 m above mean sea level in the north to about 120 m in the south (Figure 2.9). It falls within agro-ecological zone III and is characterized by sandy, arid to semi-arid conditions. The desert spans across the districts of Bhakkar, Khushab, Mianwali, Jhang, Layyah, and Muzzafargarh, all sharing similar

FIGURE 2.9 High sand dunes of the Thal Desert display the diverse landscape shaped by wind erosion.

geographical characteristics. Thal area is predominantly composed of ridges of sand dunes and rolling sand plains interspersed with narrow valleys of relatively flat, more fertile land. These sand dunes are a notable characteristic of the region, formed from sediment carried by wind and deposited by the upstream Indus River, located upstream from the mountain-building front (Munir et al., 2022). These dunes typically reach heights of approximately 175 m and cover 50–60% of the Thal Desert area. The variability in rainfall, characterized by its unpredictability and significant spatial and temporal variations, poses a major challenge to crop production in rain-fed conditions. Typically, in favorable years, dry-farmed areas yield only a moderate crop, whereas flood plains, with enhanced management practices, can produce two good crops annually. Farmers typically cultivate their lands exclusively during the rainy season, leaving them fallow for the remainder of the year (Baig et al., 2013).

Plants in the Thal Desert serve significant medicinal purposes; for instance, Harmal (*Peganum harmala*) is utilized for treating indigestion, while Kartuma (*Citrullus colocynthis*) is employed in wound care. Moreover, these plants find application in thatching huts, constructing livestock shelters, and crafting household items such as baskets and dyes. Among these, Saccharum is the most frequently utilized species due to its versatility in providing shelter, fodder, and crafting materials (Shaheen et al., 2014). In the districts of Mianwali, Bhakkar, and Khushab, agricultural wastelands are characterized by sand ridges that include longitudinal and transverse sand sheets interspersed with narrow strips of silty and clayey deposits. These sand ridges typically range from 5 to 15 m in height. In the spaces between these ridges lie hollows where rainwater runoff collects. The majority

FIGURE 2.10 *Ziziphus* shrub resiliently surviving in the harsh conditions of the Thal Desert.

of this area consists of barren wasteland with sparse vegetation comprising drought-resistant trees, shrubs, and grasses (Rahim & Hasnain, 2010). *Ziziphus* shrub is significant for desert sustainability in the Thal Desert due to its drought-resistant characteristics and ability to thrive in arid conditions. Its deep root system aids in soil stabilization and reduces erosion, contributing to habitat preservation (Figure 2.10).

2.1.5 Cold Deserts

Cold deserts, such as those found in Antarctica, Greenland, Asia, and the Nearctic realm, are characterized by harsh winters and brief, moderately warm summers (Table 2.5). These deserts are often dissected by towering mountain ranges like the Karakoram and Zanskar. The largest concentration of cold deserts worldwide is situated in Asia, encompassing the Gobi Desert (northern China and southern Mongolia), the Iranian Desert (Iran, parts of Afghanistan, and Pakistan), the Takla Makan Desert (western China), the Turkestan Desert (Middle East and southwestern Russia), and the Trans-Himalayan Desert (parts of Afghanistan, Pakistan, India, and China). The area between the Central Himalayas and the Tibetan Plateau is frequently referred to as the "Dust Bowl of India" (Chauhan et al., 2020). Twenty percent of the Earth surface is desert, with cold deserts forming a distinct biome where precipitation primarily occurs as snow or fog. The Himalayas extend across eight Asian countries: Afghanistan, Bangladesh, Bhutan, China, Myanmar, Nepal, Pakistan, and India. The high-altitude cold deserts of the Indian Himalayas cover 186,200 km^2. These regions support diverse specialized vegetation that is sparsely distributed across various habitats (Kal, 2011).

TABLE 2.5
Ecological and Environmental Characteristics of Cold Deserts

Sr. No.	Aspect	Details	Citation
1.	Ecology	Sparse vegetation adapted to arid and cold conditions, dominated by shrubs such as *Caragana, Artemisia*, and *Haloxylon* Unique fauna including snow leopards, ibex, and Tibetan wild ass	Power et al. (2024)
2.	Climate	Harsh winters with temperatures often dropping below –20°C (–4°F), occasionally much lower Short, cool summers with temperatures ranging from 10°C to 25°C (50°F–77°F). Low annual precipitation, primarily as snow and fog	Hu and Han (2022)
3.	Flora	1. *Caragana versicolor*: drought-resistant shrub 2. *Artemisia absinthium*: used in traditional medicine 3. *Haloxylon salicornicum*: important for stabilizing sand dunes 4. *Rhodiola imbricata*: adaptogen for stress relief 5. *Ephedra gerardiana*: medicinal plant for respiratory ailments	Chauhan et al. (2020)
4.	Topography	Varied terrain with high-altitude plateaus, rugged mountains (e.g., Karakoram, Himalayas), deep valleys, and occasional sand dunes. Diverse microhabitats support specialized flora and fauna	Power et al. (2024)
5.	Population dynamics	Sparse human population, including nomadic herders (e.g., Changpa people) and settled communities in oases and valleys	Karimi et al. (2021)

The understanding of species richness, distribution, and community structure in cold desert regions worldwide is limited due to their remote and inaccessible nature. Similarly, there has been little research on the structure and composition of forest resources and other management units within these cold desert environments. Sustainable management of forest resources, including practices like agroforestry and forestry systems, is crucial for enhancing the vegetation pattern, structure, and function of cold desert ecosystems. This contributes significantly to climate change mitigation, adaptation, biodiversity conservation, and the preservation of ecosystem services (Rawat et al., 2023). Most notable changes in plant community composition in cold deserts are influenced by variations in climatic conditions such as precipitation, temperature, humidity, and altitude. The diverse topography of cold deserts plays a key role in fostering species diversity and the presence of endemic species (Trigas et al., 2013).

The cold deserts of Asian countries (India and Pakistan), encompassing regions like the Trans-Himalayan belt and parts of Central Asia, present unique biomes characterized by extreme climatic conditions and minimal vegetation cover (Alqarawi et al., 2021; Negi et al., 2018). Cold deserts endure severe winters with temperatures dropping drastically below freezing, coupled with brief, moderately warm summers. Precipitation primarily occurs as snow or fog, contributing marginally to overall moisture levels. The rugged high-altitude terrain, including significant mountain ranges such as the Karakoram and Himalayas, defines the landscape of these deserts and supports a specialized array of flora and fauna adapted to the harsh environment (Tewari & Kapoor, 2013). Despite their ecological significance, these cold desert ecosystems remain inadequately researched due to their remote and inaccessible nature, underscoring the necessity for increased scientific exploration and sustainable management practices to preserve their biodiversity and ecosystem functions effectively (Siddiqui et al., 2021).

2.2 CENTRAL ASIAN DESERTS

Central Asia, characterized by its expansive arid landscapes, hosts a diverse array of deserts that exhibit unique climatic and soil salinity profiles. Among these deserts are the Turan Depression, the Gobi Desert, and the deserts of the Dzungar and Tarim depressions. Each of these regions features

distinct climatic conditions, including varying degrees of aridity and continentality, as well as different precipitation patterns. Interestingly, the extent and characteristics of salt-affected soils in these deserts do not straightforwardly correlate with their current arid climates; instead, they are influenced significantly by historical factors specific to each area. Factors such as the presence of salt-bearing rocks and the eolian migration of salts play critical roles in determining the degree and chemistry of soil salinization across these landscapes. Desert ecosystems throughout arid Central Asia face significant impacts from global change. It is crucial to comprehend the shifts within plant communities as a fundamental step toward understanding community assembly mechanisms, as well as for vegetation conservation and management (Tao et al., 2023).

A comparative analysis of the climatic and soil salinity characteristics of the deserts in Central Asia reveals distinct differences among different regions. These deserts vary significantly in terms of climatic factors including aridity, continentality, precipitation amounts, and patterns. Interestingly, there is no clear correlation between the extent of automorphic salt-affected soils and the aridity of the climate. In the automorphic landscapes of Central Asian deserts, the degree and chemical composition of soil salinization, as well as the distribution of salt-affected soils, appear to be more influenced by historical factors specific to each region rather than solely by contemporary climatic conditions. The presence and characteristics of salt-bearing rocks, as well as the eolian transport of salts, are identified as pivotal factors shaping these landscapes. The temperate desert of arid Central Asia stretches along the historic Silk Road, an ancient overland route crucial for economic and cultural exchange between East and West. This region comprises 80% of the global temperate desert area (Lu et al., 2020).

Central Asia is characterized by temperate desert and semi-desert vegetation types, prominently featuring gravel desert plants, sandy desert plants, sparse shrubs, and river valley forests (Li et al., 2020). The region encompasses diverse sub-regions with varying altitudinal belts and is bordered by some of the highest mountain ranges globally, including the Tian Shan and the Pamir. Across its altitudinal gradient, the landscape transitions from desert to mountain shrubland, followed by deciduous broad-leaved forests, dark coniferous forests, sub-alpine zones, alpine meadows, and alpine cushion vegetation (Zhang et al., 2013). Within the temperate desert biome of Central Asia, the Gurbantunggut Desert in northwest China stands out as a region that has received comparatively little research attention compared to deserts elsewhere. The vegetation is primarily characterized by co-dominant shrubs such as *Haloxylon ammodendron* and *Haloxylon persicum*, alongside ephemeral plants (Fan et al., 2014). Ephemerals play a crucial role, constituting 50% of vegetation cover and up to 70–80% of herbaceous biomass, predominantly flourishing from early spring to early summer. These ephemerals form a surface layer on the dunes, contributing significantly to sand dune stability even after they have dried up, before most deciduous shrubs and perennial herbs become green (Zhang et al., 2020).

The Gobi Desert is situated in Central Asia, spanning across northern China and southern Mongolia. It is a significant part of the arid and semi-arid region of Central Asia, characterized by its expansive desert landscapes, rocky plains, and occasional mountain ranges. The Gobi Desert, a prominent terrestrial feature in arid Asia, consists of sand dunes and weathered gravels, covering a vast area exceeding 4.0 million km^2 in central Asia. The climate in these regions is arid, with sparse vegetation leading to significant dust emissions that impact both regional and global climates (Sternberg & Edwards, 2017). The Gobi Desert zone in central and eastern Asia occupies a relatively high latitude position north of the subtropical arid zone. Its origin and development may differ from that of deserts in subtropical zones. The arid conditions in central and eastern Asia are influenced by the mid-latitude westerly circulation of the Northern Hemisphere and the Asian monsoon, respectively. These atmospheric circulation patterns and driving mechanisms vary from those observed in subtropical zones. Hence, a systematic exploration is necessary to understand the factors contributing to the formation and evolution of the Gobi Desert in this region (Lu et al., 2019).

Sand and dust storms are increasingly frequent in the arid and semi-arid regions of Central Asia, particularly around the desert zones, due to rising global temperatures. The deserts in Kazakhstan and Central Asia have a continental climate characterized by extended dry summers, powerful

winds, sparse vegetation, low soil moisture, relatively low air humidity, frequent soil waterlogging, and atmospheric dryness (Babaev, 2012). These strong winds can transport sand and dust over long distances, causing the formation of dunes, mounds, and ridges by removing particles of varying sizes through deflation. Desertification resulting from soil deflation has significantly impacted the desert and semi-desert areas of Kazakhstan and Central Asia (Issanova et al., 2023).

Given Central Asia's strategic importance within the Belt and Road Initiative, comprehending desertification processes and their ecological impacts is crucial for achieving sustainable development objectives in the region (Li et al., 2023). Ephemeral plants play a crucial role in northern temperate desert plant communities by significantly contributing to species diversity and herbaceous layer productivity (Qiu et al., 2007). In the Gurbantungut Desert of central Asia, they comprise over 40 species, amounting to approximately one third of the desert's total plant diversity. This broad diversity and widespread distribution of plant types biologically enhance soil nutrient cycles, mitigate desertification and sandstorms, and consequently enhance ecosystem stability in the Gurbantungut Desert (Mu et al., 2023).

2.3 ARABIAN DESERTS

The continental interiors of arid tropical regions often feature extensive dune fields that blanket the landscape. These sand seas are composed of countless detrital grains that faithfully record their origin and evolution over time and space. However, interpreting these vast repositories of geological information is challenging. The paths along which sediment is dispersed are intricate and variable due to wind transport, which is not governed directly by gravity. This variability occurs repeatedly in response to both seasonal fluctuations and long-term changes in climate (Garzanti et al., 2013). Arabic deserts are characterized by diverse topographic factors that shape their unique landscapes and ecosystems. These deserts encompass a variety of types, each influenced by distinct geographical features such as vast sand seas, rocky plateaus, rugged mountains, and expansive gravel plains. The topography plays a critical role in determining the desert climate, water availability, and biodiversity. From the vast dunes of the Rub' al Khali in the Arabian Peninsula to the rugged mountains of the Sinai Desert in Egypt, each desert type presents its own challenges and opportunities for life and adaptation. The topographic factors are essential for comprehending the ecological dynamics and human interactions within Arabic desert environments.

The Eastern Desert of Egypt stretches between the Nile Valley and the Red Sea, intersected by numerous canyon-like depressions known as wadis that lead either to the Red Sea or the Nile Valley. Among these features, Wadi Al-Assiuty stands out as one of the most prominent in the Eastern Desert. This wadi is the largest and longest dry valley in the Sahara Desert, extending approximately 115 km in length with a width varying from 5 to 25 km. While typically dry throughout the year, Wadi Al-Assiuty experiences seasonal rainfall during winter, occasionally becoming torrential in autumn and spring (Salama et al., 2014). The Middle East exhibits a varied landscape that includes expansive gravel and sandy deserts, elevated plateaus, and mountain ranges. Positioned on the periphery of a significant tectonic plate, the region is characterized by the Arabian Peninsula drifting away from Africa, while portions of the Anatolian Peninsula (Turkey) slide alongside parts of Asia. The Arabian Peninsula is situated between the Red Sea and the Persian Gulf and is distinguished by extensive areas of gravel and sand deserts. Among these, the Arabian Desert stands as one of the planet's largest, spanning from Yemen to the Persian Gulf and from Oman to Jordan and Iraq. A significant portion of this desert, predominantly in southern Saudi Arabia, constitutes the hyper-arid Ar Rub' Al Khali, also known as the Empty Quarter. This region is renowned for its vast stretches of linear sand dunes, some extending over 25 miles in length. To the north lies Ad Dahna', which links to the Nafud Desert in western Saudi Arabia. The Nafud Desert is characterized by immense sand dunes, with some towering more than 30 m in height (Ghazanfar & McDaniel, 2016).

The arid desert climate of the Arabian Peninsula is marked by elevated temperatures, sporadic and minimal rainfall, and substantial evaporation rates. Factors like intense solar radiation and soil

salinity further influence the survival strategies of plant species. Each desert plant species possesses unique adaptations aimed at maximizing reproductive success within this harsh environment (Bhatt et al., 2016). In Saudi Arabia, where desert landscapes dominate over 70% of the biomes, significant changes in land use and cover have occurred over the past three decades. This transformation coincides with an intensive development program fueled by substantial oil revenues. Saudi Arabia is renowned for its rapid urban expansion within the Middle East region (Mubarak, 2004). This expansion has altered various environmental aspects such as landscape ecology, hydrological processes, climate systems, and patterns of land cover. However, due to inadequate planning frameworks and insufficient consideration of potential negative impacts, unchecked development has led to excessive growth and subsequent degradation of the desert ecosystem (Alqurashi & Kumar, 2014).

The Wadi Araba desert ecosystem in southwest Jordan hosts a unique blend of Saharo-Arabian vegetation, influenced by African plant species, and sustains a community of local nomads primarily engaged in herding. Many of these nomads face economic hardship, with their income often falling near or below the poverty line (Al-Assaf et al., 2022). Despite these challenges, the fragile vegetation in this area continues to provide essential services such as firewood, animal feed, medicinal resources, and food. Several plant species native to this region are classified as vulnerable or endangered according to the Jordanian IUCN list of threatened plants. Because of the challenges of poverty, climate change, and recent economic downturns worsened by the pandemic, it is crucial to prioritize the development of small-scale projects that benefit both the local community and the ecosystem (Albalawneh et al., 2022).

The medicinal plants of the Arabian Desert are of significant importance due to their rich bioactive chemical composition and pharmacological actions (Table 2.6). These plants have been traditionally used by local communities for centuries, showcasing diverse therapeutic properties such as anti-inflammatory, antimicrobial, antioxidant, and analgesic effects (Almoshari, 2022). Examples include species like *Rhazya stricta, Withania somnifera*, and *Commiphora* spp., which contain bioactive compounds such as alkaloids, flavonoids, terpenoids, and phenolic acids. These compounds contribute to their medicinal properties, making them valuable sources for drug discovery and development (Qari et al., 2021). Research on Arabian Desert medicinal plants continues to explore their potential in treating various ailments and addressing health challenges, highlighting their importance in both traditional and modern medicine systems (El-Seedi et al., 2022).

2.4 AFRICAN DESERTS

African deserts, renowned for their striking beauty and severe conditions, represent some of the continent's most extreme and fascinating terrains. These arid regions are defined by minimal rainfall, high temperatures, and expansive, open areas. Despite these harsh elements, they host a variety of specialized flora and fauna that have evolved to thrive in such a demanding environment. African deserts are not merely geographic features; they also embody cultural and ecological systems that profoundly influence the people and wildlife inhabiting them.

Among the prominent deserts in Africa are the Sahara, the largest hot desert in the world, extending across North Africa and covering numerous countries; the Kalahari, which spans Botswana, Namibia, and South Africa and is noted for its vast salt pans and rich biodiversity; and the Namib, one of the planet's oldest deserts, situated along Namibia's coast and famous for its dramatic red dunes and coastal mist. Each of these deserts has its own unique attributes, contributing to the diverse and intricate landscape of African desert regions.

2.4.1 Sahara Desert

When imagining a desert, the typical image that comes to mind is often of vast sand dunes stretching endlessly, evoking a sense of emptiness and desolation. However, deserts vary greatly in their landscapes. Many are characterized by mountainous terrain or rocky surfaces. For instance, much

TABLE 2.6
Dominant Plant Species in the Arabian Desert: Taxonomy, IUCN Status, and Habitat

Sr. No.	Botanical Name	Common Name	IUCN Category	Habit	Habitat
1.	*Rhazya stricta* Decne. ex Steud.	Arabian mistletoe	Least Concern	Shrub	Desert, Semi-desert, Sand dunes
2.	*Withania somnifera* (L.) Dunal	Ashwagandha	Not Evaluated	Shrub	Desert, Dry forests
3.	*Commiphora wightii* (Arn.) Bhandari	Indian bdellium	Vulnerable	Shrub	Arid woodlands, Scrub forests
4.	*Calotropis procera* (Aiton) W.T. Aiton	Sodom apple	Least Concern	Shrub	Desert, Sand dunes
5.	*Ziziphus spina-christi* (L.) Desf.	Christ thorn jujube	Least Concern	Tree	Arid woodlands, Scrub forests
6.	*Acacia ehrenbergiana* Hayne	Salam tree	Least Concern	Tree	Desert, Sand dunes
7.	*Artemisia herba-alba* Asso	White wormwood	Least Concern	Shrub	Desert, Semi-desert
8.	*Citrullus colocynthis* (L.) Schrad.	Bitter apple	Least Concern	Herb	Desert, Sand dunes
9.	*Echinops spinosissimus* Turra	Thorny globe thistle	Least Concern	Herb	Desert, Semi-desert
10.	*Fagonia indica* Burm.f.	Dhamasa	Least Concern	Shrub	Desert, Semi-desert
11.	*Aerva javanica* (Burm.f.) Juss. ex Schult.	Kapok bush	Least Concern	Herb	Desert, Sand dunes
12.	*Launaea mucronata* (Willd.) Amin ex C.Jeffrey	Wild lettuce	Least Concern	Herb	Desert, Semi-desert
13.	*Nitraria retusa* (Forssk.) Asch.	Nitre bush	Least Concern	Shrub	Desert, Coastal regions
14.	*Panicum turgidum* Forssk.	Turgid desert grass	Least Concern	Grass	Desert, Sand dunes
15.	*Pulicaria crispa* (Forssk.) Oliv.	Crisped fleabane	Least Concern	Herb	Desert, Semi-desert
16.	*Rhanterium epapposum* Oliv.	Yellow chamomile	Least Concern	Shrub	Desert, Semi-desert
17.	*Salsola imbricata* Forssk.	Saltwort	Least Concern	Shrub	Desert, Sand dunes
18.	*Salvadora persica* L.	Toothbrush tree	Least Concern	Shrub	Desert, Dry forests
19.	*Suaeda aegyptiaca* (Hasselq.) Zohary	Seablite	Least Concern	Shrub	Desert, Coastal regions
20.	*Tamarix aphylla* (L.) H.Karst.	Athel tamarisk	Least Concern	Tree	Desert, Riverbank

of the Sahara Desert is a plateau with a rocky surface, featuring exposed horizontal bedrock and, in some areas, scattered boulders or smaller rocks (Laity, 2009). The Sahara Desert, covering 10% of the African continent, is the largest hot desert in the world. The Algerian portion of the Sahara spans around 2 million km^2, accounting for 85% of Algeria's land area, and is renowned for its severe aridity. Despite its extensive size, the Algerian Sahara has relatively low species diversity and endemism, with roughly 1,200 plant species recorded. Vegetation within the Sahara is sparse, discontinuous, and irregular, with plant life predominantly confined to areas where water availability is somewhat more favorable compared to other parts of the desert (Bradai et al., 2015).

The Sahara Desert extends across the northern third of Africa, from the Atlantic Ocean to the Red Sea. The region is marked by extremely low and variable precipitation, high temperatures, significant temperature fluctuations, and prolonged droughts, creating harsh environmental conditions that challenge the survival of many organisms (Bouallala et al., 2020). Annual rainfall is minimal yet adequate to sustain plant life across most of the northern Sahara Desert. The vegetation is highly variable, with density and structure dependent on the specific environmental conditions of each

area. Vegetation tends to be denser in depressions, and wadi beds are more sparse, with low canopy cover on desert plateaus, pavements, and sand dunes (Azizi et al., 2021).

The natural vegetation in this region, which includes wild-grown plants, serves as the primary forage for dromedaries in extensive husbandry and free-grazing systems. The climate is characterized as hyper-arid desertic, with significant variability in precipitation both inter-annually and intra-annually, which occurs solely as rainfall (Chehma et al., 2008). The region experiences high temperatures, a wide range of temperatures, intense evapotranspiration, prolonged droughts, and extreme weather events such as heat waves and severe winds. Rainfall is very limited, ranging from less than 36 to 76 mm per year, with fewer than 12 days of effective rainfall annually. Potential evapotranspiration consistently exceeds precipitation throughout the year. July is the hottest month, with average maximum temperatures exceeding 41°C, while in January, minimum temperatures remain above 3.2°C–4.4°C. The area enjoys high monthly sunshine frequency, exceeding 70% (Bradai et al., 2015).

The harsh climatic conditions of hot drylands, such as extreme temperature fluctuations and irregular, minimal rainfall, are significant ecological factors that shape the distribution and composition of vegetation communities in the Sahara Desert. Vegetation primarily thrives in mesic habitats, such as oases and wetlands, where the availability of water and better soil conditions facilitate plant establishment. Extensive research on Sahara Desert flora has been conducted across various habitats and landscapes, including wetlands near oases in hyper-arid regions. Approximately 3,000 plant species, including 2,800 flowering plants, have been documented in this ecoregion (Bouallala et al., 2020).

Covering more than two-thirds of the Sahara Desert Algerian territory, the arid and semi-arid regions are vital natural resources that warrant significant attention. The conservation of these ecosystems relies on a deeper understanding of their biological diversity, particularly the wild plants that have evolved unique qualities and adaptations to survive the extreme environmental conditions over millennia (Malika et al., 2015). Given the limited information available on the biodiversity of native flora in these northern Sahara arid regions, there is a strong emphasis on studying the distribution of natural vegetation. This survey aims to explore the relationship between vegetation and arid soil and to define the distribution patterns of wild plants. The region has experienced severe vegetation degradation due to prolonged desertification, driven by factors such as drought, overgrazing, and overharvesting. This information is essential for developing effective strategies, programs, and technical guidelines for the conservation and sustainable management of natural resources (Table 2.7).

In the Sahara Desert of Algeria, scientists studied the variety of pollen in honey to better understand how bees interact with the sparse plant life in this arid environment. They analyzed honey samples to see how different factors affect pollen diversity, including the climate zones, honey extraction methods, bee breeds, and beekeeping practices on the complex relationship between bees and the unique plant life of the Algerian Sahara (Bouallala et al., 2023). It emphasizes the role of melissopalynological analysis in understanding honey quality and improving beekeeping practices and highlights the importance of conserving plant-pollinator interactions in extreme environments. Future research will be crucial for better managing and protecting biodiversity in such harsh conditions (Laallam & Chenchouni, 2024).

2.4.2 Namib Desert

The Namib Desert is an elongated, narrow coastal desert extending from southern Angola to just north of Cape Town, South Africa, with its central area focused on the Namib Desert Sand Sea (Mitchell et al., 2020). The hyper-arid Namib Desert, situated along the western shore of southern Africa adjacent to the South Atlantic Ocean, is a distinct, cool coastal desert. It extends longitudinally over 2000 km from northern South Africa to southern Angola and spans less than 140 km in width. The Central Namib is noted for its extensive gravel plains, which are demarcated to the south by the ephemeral Kuiseb River from the Namib Sand Sea, a U.N.E.S.C.O. World Heritage site. The

TABLE 2.7
Geomorphological Features and Flora of the Sahara Desert Regions

Erg Chebbi	*Barchan dunes*: Crescent-shaped, predominant in this area	*Dune slopes*: Vegetated with specialized plants *Oases*: Found at the base of dunes	*Flora*: Includes desert grasses and hardy shrubs	*Date palm* (*Phoenix dactylifera*): Provides fruits and shade *Saharan cress* (*Lepidium sativum*): Edible leaves
Erg Admer	*Star dunes*: Multi-armed dunes with complex patterns	*Rocky outcrops*: Shelters for various species *Small oases*: Sparse but important	*Flora*: Limited, with some hardy grasses and xerophytes	*Wild melon* (*Citrullus colocynthis*): Bitter but useful in survival
Hamada El Hamra	*Minimal dunes*: More stony terrain than dunes	*Rock crevices*: Provide habitat for plants and animals	*Flora*: Sparse, with some xerophytic plants like tamarisk	*Camel thorn* (*Alhagi maurorum*): Edible parts and useful for camel fodder
Tassili n'Ajjer	*Linear dunes*: Long, parallel ridges along the mountain base	*Canyons and rock shelters*: Unique habitats for both flora and fauna	*Flora*: Includes ancient trees and specialized shrubs	*Tamarisk* (*Tamarix* spp.): Provides edible parts and shelter
Chott El Jerid	*Minimal dunes*: More salt crusts than sand dunes	*Salt Crusts*: Harsh, with very specialized flora *Oases*: Often found around the periphery.	*Flora*: Halophytes and salt-tolerant plants like saltwort	*Saltwort* (*Salsola* spp.): Edible and used for survival
Siwa Oasis	*Minimal dunes*: Predominantly oasis environment rather than dunes	*Oases*: Rich in vegetation, with agriculture possible due to available water	*Flora*: Includes date palms and other fruit trees	*Date palm* (*Phoenix dactylifera*): Key food source and economy resource

edaphic conditions in these desert systems differ significantly: the gravel plains feature relatively stable surfaces with rock outcrops and pebbly "desert armor", while the Sand Sea is characterized by vast expanses of wind-blown sand and dynamic aeolian dunes. These deserts function as water pulse system-driven environments (Cowan et al., 2020). The arid west coast of the southern African subcontinent experiences infrequent precipitation due to its location in the descending limb of the Hadley Cell, a component of the Global Circulation System. This results in a pronounced NE–SW rainfall gradient across southern Africa, transitioning from the semi-arid conditions of the Kalahari and Karoo to the hyper-arid environment of the Namib coast (Eckardt et al., 2013).

Namibia is the most arid nation in Southern Africa, with limited water resources for crop-based agriculture necessitating substantial food imports. Despite this, the country benefits from a distinctive coastal desert environment characterized by cool temperatures, intense sunlight, and frequent fog, which could support climate-smart agricultural practices in the Namib Desert (Geyh & Heine, 2014). Research in this desert has predominantly focused on animal and plant ecology. The Namib Desert is notable for its unique setting along the Atlantic Ocean, where the Benguela upwelling system enhances oceanic primary production through the upwelling of nutrient-rich waters driven by trade winds. As one of the world oldest deserts, the Namib has experienced hyper-arid conditions for approximately 5 million years, with geological evidence indicating that aridity may have begun around 65 million years ago (Mupambwa et al., 2019).

Global and regional climate models project that Namibia will experience progressively higher temperatures and reduced rainfall throughout the 21st century, leading to severe environmental impacts. This warming and drying trend is expected to result in the migration of arid-adapted

species into more mesic regions (Rohde et al., 2019). In the Namib Desert, calcrete crusts are formed in situ through the atmospheric precipitation of calcium carbonate in the arid environment. These calcretes cover extensive areas of the Angolan Namib, where the plains are typically barren except for sparse dwarf shrubs and resilient grasses. However, following episodic rain showers, which can bring 10 to 50 mm of precipitation over just a few days, the gravel plains become verdant with the rapid growth of annual grasses such as *Aristida, Schmidtia,* and *Stipagrostis* (Huntley, 2023).

Although deserts generally exhibit lower species richness, their extreme conditions foster high levels of specialization and endemism. For instance, endemism is notably high in the Namib Desert (34.5%), the Atacama Desert (60%), and the desert regions in the Horn of Africa (55%) (Mittermeier et al., 2004). Unlike the perennial shrubs, grasses, and trees typical of savannas, deserts are predominantly characterized by succulents and rosette plants. In the context of paleoclimatology and levels of endemism, the region extending from the Namib Desert to the Kalahari has recently been recognized as a potential source area for the colonization of the relatively younger and less arid inland habitats (Nylinder et al., 2016).

Welwitschia mirabilis Hook.f. is considered a living fossil, representing an ancient lineage of gymnosperms, and serves as a key symbol of the biodiversity in the Namib Desert. This species exhibits a distinctive morphology as a long-living dwarf tree with only two leaves that continuously grow throughout its lifespan (Bombi, 2018). It is a keystone species within Namib Desert ecosystems, providing essential resources such as food, water, and shelter for various animal species, including mammals, reptiles, and insects. *W. mirabilis* is endemic to the central and northern regions of the Namib Desert, with its distribution extending from the Kuiseb River in Namibia to the Nicolau River, north of Namibe, in Angola (Bombi et al., 2021).

2.5 EUROPEAN DESERTS

Europe might not be the first place that comes to mind when you think of deserts, but it does host a few unique arid landscapes. These regions are characterized by their sparse vegetation, low precipitation, and extreme temperatures. Notable European deserts include the Tabernas Desert in Spain, which is the only true desert in mainland Europe, and the Bardenas Reales in Spain, a semi-desert that features striking geological formations. Moreover, the Accona Desert in Italy and the Crau Plain in France represent arid regions with distinct ecological and geological features. Each of these areas showcases the diverse and sometimes surprising arid environments that exist across the European continent.

Soil is one of the richest ecological niches for microbial bioprospecting, including in drylands. While drylands are among the most widespread biomes globally, true desert environments are relatively rare in Europe. One notable exception is the Tabernas Desert in the province of Almería in southeastern Spain, which represents one of the few desert regions in continental Europe. This region is characterized by its marl and sandstone formations, as well as sparse vegetation. With annual precipitation of less than 250 mm, the climate ranges from hot semi-arid to desert, depending on the altitude. Furthermore, the desert features notable and well-developed biocrusts (Molina-Menor et al., 2021).

Dew deserts, similar to fog deserts, can offer a consistent water source to various organisms during the dry season. This supplementary moisture can support the survival of diverse organisms that might otherwise struggle to survive or exhibit significantly reduced biomass in such extreme arid conditions (Uclés et al., 2016). Another potential candidate for a dew desert is the southeastern Iberian Peninsula, which encompasses the Tabernas Desert. Situated 20–60 km from the Mediterranean Sea and receiving an average annual precipitation of 200–240 mm, dew is believed to significantly influence the water balance in the Tabernas Desert. It has been reported to positively affect the water availability for various organisms, including plants (Kidron & Lázaro, 2020).

The badlands of Tabernas are frequently cited by the media as an example of desertification in Spain. However, this representation involves two key misconceptions (Martínez-Valderrama et al.,

2020). Firstly, Tabernas does not qualify as a true desert because it does not meet the climatic criteria typically used to define desert environments. Secondly, associating an erosive landscape with desertification overlooks the actual causes of land degradation in the region. Since the mid-1990s, there has been a growing demand for irrigated water in Almería to support various crops, including high-density olive production (Downward & Taylor, 2007).

The Tabernas Desert, located in the Almeria province of southeastern Spain on the Iberian Peninsula, is situated in the central part of a tectonic basin that was filled with marine marls (or calcareous-gypsiferous mudstones) and turbidites during the Upper Miocene. This basin also contains occasional interbedded calcareous sandstones found in peripheral areas, representing the continental talus of the Miocene Sea. The region enjoys over 3000 hours of sunshine annually, with mean annual temperatures ranging from 17° to 19°C. Monthly temperature fluctuations average 14°C. Frosts are infrequent but may occur from November to March. Relative humidity averages between 52% in summer and 66% in winter, though daily variations are significantly greater than seasonal changes. The average annual potential evapotranspiration is 1666 mm (Lázaro et al., 2022). The Tabernas Desert in southeastern Spain is a delicate ecosystem situated over Miocene gypsum-calcareous mudstones. This region has been characterized by the development of badlands since at least the early Holocene, resulting in one of the most extensive badlands in Europe. The landscape features a complex patchwork of various plant-covered areas and exposed ground, each exhibiting distinct hydrological and erosive properties (Cantón et al., 2003).

The Tabernas Desert spans approximately 150 km^2 and is home to one of the best-preserved badlands in the Mediterranean region. In addition to its significant geological interest, the desert features unique ecological attributes, including rare endemic plant species and biocrusts. However, a portion of this area lacks specific protection for its diverse geological features. Recently, the high number of annual sunshine hours has attracted solar power projects from major corporations, raising concerns about the potential impact on this distinctive landscape (Solé-Benet et al., 2022). In the Tabernas Desert the dominant vegetation consists primarily of xerophytic and drought-resistant species adapted to the arid conditions. Key plant species include the evergreen shrubs *Retama sphaerocarpa* and *Ziziphus lotus*, which are well-suited to the low water availability and high temperatures (Cai et al., 2020). Furthermore, *Artemisia herba-alba* and *Erodium cicutarium* are common, contributing to the desert's distinctive plant community (Sánchez et al., 2022).

2.6 LATIN AMERICAN DESERTS

Latin American deserts are unique landscapes characterized by their extreme aridity, diverse ecosystems, and striking geological formations. Located primarily along the western coast of South America and extending into parts of Mexico and Central America, these deserts exhibit a range of features that contribute to their distinct environments. From the vast sand dunes of the Atacama Desert in Chile, known for being one of the driest places on Earth, to the rugged terrain of the Sonoran Desert spanning Mexico and the southwestern United States, Latin American deserts offer a variety of habitats that support specialized flora and fauna. Key features of these deserts include sparse vegetation, unique adaptations of plant and animal life to extreme conditions, and dramatic landscapes shaped by wind and erosion. The types and characteristics of American deserts provide insight into the remarkable resilience of life in some of the harshest climates on the planet. American deserts, stretching across the southwestern United States and northern Mexico, are defined by their extreme aridity and remarkable adaptability of flora and fauna. These arid landscapes feature sparse vegetation, dramatic geological formations, and significant temperature fluctuations, with each desert exhibiting unique characteristics and ecosystems. Among these, the Chihuahuan Desert stands out for its rich biodiversity and distinctive plant life, including the resilient lechuguilla and various species of agave. This desert is the largest in North America and is characterized by its varied terrain, from rugged mountains to expansive plains, and its role as a crucial habitat for a wide range of desert-adapted species.

2.6.1 Atacama Desert

The Atacama Desert in northern Chile is recognized as the oldest and driest desert on Earth, having developed over 100 million years of aridity and 10–15 million years of extreme hyper-aridity (Gómez-Silva, 2010). In the hyper-arid core of the desert, particularly the Yungay region, the average annual rainfall is less than 2 mm, with extended periods of no precipitation. Other areas within the desert are marked by extensive salt flats, such as the Salar de Atacama, which contains lagoons with varying brine compositions, and are bordered by high-altitude plateaus like the Puna de Atacama. The availability of liquid water and high solar radiation are key environmental factors influencing microbial colonization in the Atacama Desert (Bull & Asenjo, 2013). The Atacama Desert is bordered by the Andes Mountains to the east and the Pacific Ocean to the west, exhibiting a distinctive array of environmental extremes, including severe dryness, the highest ultraviolet radiation levels globally, and highly saline and oxidizing soils. These conditions have made the Atacama a prime candidate for research as a Mars analog over the past two decades. Given its extreme water scarcity and its relevance to Martian conditions, two key ecosystems within the Atacama are of particular interest: the coastal range and the ultra-dry hyperarid core (Azua-Bustos et al., 2022). Covering approximately 180,000 km^2, the Atacama Desert is a coastal desert that, along with the broader Atacama region, encompasses a vast array of ecological niches. Historically known for its mineral resources, the Atacama Desert is home to a diverse range of microbial life, much of which has only recently been discovered. A significant portion of this microbial diversity remains uncultured and taxonomically unidentified (Bull et al., 2016).

Despite being one of the driest places on Earth, the Atacama Desert supports a unique and diverse flora that is highly adapted to its hyper-arid conditions. Vegetation is generally limited to the desert margins, specifically along the Andean range to the east and the Pacific coastal range to the west, with only occasional exceptions found in riverbeds or canyons (Ruhm et al., 2020). On the western slopes of the Andes, the Atacama Desert ecosystems, which range from hyper-arid to high Andean environments, span an elevational gradient of over 6,000 m. This extensive range includes notable variations in precipitation and temperature over relatively short distances (~300 km). The elevational gradients are crucial for examining the climatic and evolutionary factors that influence biodiversity (Díaz et al., 2012). The elevation gradient, along with its interaction with increasing rainfall and decreasing temperatures (as well as other factors like grazing or human impact), result in distinct vegetation belts that can be consistently identified across the region based on plant physiognomy. However, the species assemblages within these belts may be ephemeral or exhibit anomalies over extended time periods. Despite this, the current distribution of flora serves as a reference point for comparing vegetation and assessing the degree of similarity or changes over time based on the paleo record (Díaz et al., 2019).

Although the Atacama Desert environment is highly favorable for studying the interactions between prehistoric societies and their landscapes, considerable research remains to be done to fully understand these relationships. Large portions of the hyper-arid core of the Atacama Desert, previously assumed to be too inhospitable for human settlement, have not been thoroughly surveyed for archaeological evidence. The cultures established diverse social systems, which evolved over time in terms of their social, economic, and ideological structures (Workman et al., 2020). The Atacama Desert, the driest nonpolar region on Earth, provides a distinct opportunity to investigate plant adaptations to severe environmental conditions. This study demonstrates how major plant lineages in the Atacama Desert exhibit adaptive strategies, such as the enhancement of plant growth-promoting bacteria in their rhizospheres and the positive selection of genes linked to crucial survival processes (Eshel et al., 2021).

The Atacama Desert periodically experiences a dramatic surge of life and color in a phenomenon known as the flowering desert (FD), which occurs when dormant desert plants rapidly bloom in response to precipitation. The FD events have significant ecological, social, and economic impacts on the Atacama region. They activate trophic networks within the desert, including herbivores and

pollinators, which in turn support tourism and domestic livestock. The latter relies on this brief period of heightened plant productivity for its sustenance (Astorga-Eló et al., 2020). In the Atacama Desert of northern Chile (19–24°S), *Prosopis* (Leguminosae) trees are confined to oases that are unevenly distributed and separated by extensive barren landscapes. This distribution provides a valuable model for studying how the degree of connectivity between natural populations is influenced by their dispersal abilities and the landscape barriers. This basin has been home to several human settlements since the Late Pleistocene and is linked by a small ravine to the lower course of the Loa River, near its mouth on the Pacific Coast (Bessega et al., 2021).

2.6.2 Sonoran Desert

Desert shrublands, primarily composed of long-lived shrubs (and cacti in subtropical areas) and extensive barren soil, dominate the lowest elevations (< 1,200 m above sea level) in the region. These shrublands expanded during the Holocene as temperatures rose and precipitation decreased, with many species extending their northern ranges only in the past few millennia. While historical evidence is limited, it is generally believed that the sparse distribution of plants and lack of continuous fuel make these desert shrublands largely resistant to fire, particularly in hot subtropical deserts (Mojave, Sonoran, and Chihuahuan), where fire-adapted species are scarce. The prevalence of barren ground may also be attributed to the relatively recent emergence of desert shrublands and the slow migration and establishment of perennial plants capable of utilizing the available space and resources (Wilder et al., 2021).

The Sonoran Desert spans approximately 260,000 km^2 across the states of Baja California, Baja California Sur, and much of Sonora, extending into parts of Arizona and California in the United States. This desert supports a diverse array of flora and fauna, including numerous shrubs and cacti. Among its notable species is the saguaro (*Carnegiea gigantea*), a columnar cactus that serves as an indicator species for the Sonoran Desert (López Reyes, 2001. In the northwestern region of the Sonoran Desert, annual rainfall is less than 50 mm, though it can reach up to 250 mm in the plains of Sonora. Despite the limited rainfall and extreme summer temperatures exceeding 45°C, the Sonoran Desert is the wettest and hottest, and likely the most botanically diverse desert in the world (Zolotokrylin et al., 2020). Within the Sonoran Desert, there are only a few studies that have examined how climate change affects the phenology of native plant species. Much of the research on the phenological impacts of climate change builds on studies conducted nearly 30 years ago, which focused on identifying the flowering triggers and developmental needs of key woody species in the Sonoran Desert (Zachmann et al., 2021).

The Sonoran Desert is a resource-abundant environment with a long history of human occupation by both foraging and agricultural societies throughout the Holocene. It contains the oldest evidence of maize agriculture north of Mesoamerica and saw the development of extensive agricultural settlements in its well-watered areas during the pre-Hispanic period. Hundreds of plant species were at least harvested from the wild, and some may have been domesticated or cultivated. For instance, *Agave* species such as *Agave murpheyi* (Hohokam agave) and *Agave delamateri* (Tonto Basin agave) were domesticated and extensively cultivated by indigenous peoples in Arizona. Moreover, mesquite (*Prosopis glandulosa*, *Prosopis velutina*, and *Prosopis pubescens*) was one of the most widely utilized wild-harvested food plants in the Sonoran Desert (Flower et al., 2021).

As climate change progresses, spring-fed habitats face growing vulnerability to various threats. Botanical inventories are crucial for evaluating the conservation value of desert springs. They can also serve as indicators for monitoring changes in conditions, such as the ratio of native to non-native species, the diversity of life forms that affect ecosystem structure and function, species persistence and longevity, and the proportion of rare and sensitive taxa impacted by land use changes (Fraga et al., 2023). Despite the Sonoran Desert's rich biodiversity, land degradation is intensifying, primarily due to rapid population growth and the significant imbalance between water demand and the limited supply. Overexploitation of aquifers and state policies have increasingly prioritized social

demands over water availability. These policies have favored the development of resorts, urban expansion, and coastal zone encroachment, driven by economic growth theories while neglecting the limited water resources required to sustain such development. Furthermore, the cultivation of water-intensive crops exacerbates agricultural land degradation through increased evaporation and soil salinization. To address these issues, the Water Agenda 2030 proposes importing water from other regions (Rodriguez-Iturbe et al., 2001).

During the monsoon season in the Sonoran Desert, where the Comcáac (Seri) Indigenous people live, desert plants release a variety of terpenes; natural compounds found in over 60 plant species that collectively produce 115 distinct biogenic volatile oils. The compounds have been shown to support human health. These terpenes potentially improve sleep patterns, regulate emotional hormones, aid digestion, alleviate depression and anxiety, and prevent diseases related to oxidative stress. Furthermore, in the Sonoran Desert, these biogenic organic compounds may contribute to overall well-being (Estrada-Castillón et al., 2022). First-time visitors to the Sonoran Desert are often impressed by the stark contrast between its arid landscape and the lush greenery found in many other regions of the United States. Despite its seemingly barren appearance during certain times of the year, the Sonoran Desert is rich in food resources (O'Brien Cherry, 2014).

The Sonoran Desert is the most biodiverse desert in the United States, hosting over 3,000 plant species uniquely adapted to its arid conditions. This includes more than 300 species of cacti, along with other succulents, woody shrubs, and herbaceous plants. Cacti, in general, are prevalent across deserts in the Americas, with various species adapted to endure extreme temperatures and dryness. Among them, the saguaro cactus (*C. gigantea*) is one of the most extensively researched plants globally, with considerable knowledge about its establishment, abundance, and ecological role (Bilderback et al., 2021). Within the Sonoran Desert of the southwestern United States and Mexico, there are 18 species of prickly pear. Notable species commonly cultivated in the Sonoran and Mojave Deserts include the Engelmann prickly pear, Santa Rita prickly pear, Indian fig prickly pear, and Beavertail prickly pear (Wilson et al., 2019). At the start of the 21st century, the southwestern United States experienced a severe drought that led to significant die-offs among many plant species. In the northwestern Sonoran Desert, this drought caused severe desiccation and mortality in cholla (*Cylindropuntia*) cacti. Variations in mortality rates among different species at various elevations were attributed to factors such as intra- and interspecific competition, reproductive strategies, and shoot architecture. Research suggests that *Cylindropuntia* species undergoes periodic, extensive die-offs in response to extreme droughts, whereas the populations of the other three species show relatively stable numbers during such events (Bobich et al., 2014).

2.6.3 Chihuahuan Desert

The Chihuahuan Desert is the largest and most diverse arid desert in North America. The geological and climatic events of the Miocene-Pliocene, along with the cyclical climatic changes of the Pleistocene, significantly influenced the diversity patterns of species within this desert (Scheinvar et al., 2020). Approximately 4,000 years ago, the Chihuahuan Desert, which is the second most diverse desert globally, with around 3,400 plant species, was characterized by significant ecological features. This region, noted for its high cactus diversity, includes nearly 25% endemic species, particularly in the Cuatro Ciénegas Basin, which hosts 86 unique plant taxa. The climate is predominantly hot and dry with summer rainfall. The area mainly consists of calcareous soils, though there are notable gypsum outcrops scattered throughout the region (Zavala-Hurtado & Jiménez, 2020). The Chihuahuan Desert, situated in southwestern United States and northwestern Mexico, lies at the climatic boundary between the subtropical and mid-latitude regions. It features a semiarid climate with relatively cool, dry winters and warm, wet summers (Rivera et al., 2010).

The Chihuahuan Desert spans approximately 505,000 km^2. It extends between 22° and 32° N latitude and 100–108° W longitude, covering parts of the Mexican states of Chihuahua, Durango, Zacatecas, Nuevo León, and San Luis Potosí, as well as regions in the southern United States,

including New Mexico, Arizona, and Texas. This arid region is noted for its high biodiversity and unique endemic plant species. In the northern parts of the Chihuahuan Desert, temperatures are higher and winters are drier, while the southern areas experience less extreme aridity (Vásquez–Cruz & Sosa, 2020). The Chihuahuan Desert is recognized for its high biodiversity, but there has been limited research specifically targeting the vascular flora in its localized regions (González–Zamora et al., 2020). The Chihuahuan Desert, and the Cuatro Ciénegas Basin in particular, are well-known for their exceptional environmental and specific biodiversity. The general aridity of the Chihuahuan Desert is characterized by a brief and sparse summer rainy season, overlaying a unique geology dominated by gypsum soils. Moreover, montane sky islands within the desert host relict populations of temperate vegetation that once covered the Mexican Plateau (Ezcurra et al., 2020). The Chihuahuan Desert is an ecoregion stretching nearly 1500 km from just south of Albuquerque, New Mexico, to the Trans-Mexican Volcanic Belt. The variation in vegetation and typical climate across this desert contribute to its status as one of the most biodiverse arid deserts globally, with numerous taxa classified as at risk, including some that are critically endangered (Zacarías-Correa et al., 2020). The region is predominantly composed of sedimentary rocks, with smaller occurrences of extrusive and intrusive igneous and metamorphic rocks, which are exposed in the mountainous areas. These rocks date from the Upper Paleozoic to the Upper Jurassic and Cretaceous periods. In contrast, the lowland areas are primarily covered by Quaternary alluvium, while the foothills and transitional zones are characterized by polymictic conglomerates from the Pliocene and Holocene epochs (Giménez de Azcárate et al., 2023).

The Chihuahuan Desert is the most biologically diverse desert in the Western Hemisphere and ranks among the most diverse arid regions globally. It is particularly noted for its exceptional plant diversity. This ecoregion is distinguished by a high level of endemism, hosting over 670 plant species and nearly half of its freshwater fish species that are found exclusively here. However, the Chihuahuan Desert is threatened by various factors, including habitat loss and fragmentation, climate change, shifting wildfire patterns, and the degradation of freshwater resources. A recent study identified 67 families, 263 genera, 671 species, and 155 infraspecific taxa (comprising 73 subspecies, 79 varieties, and three hybrids) of endemic plants, totaling 826 taxa (Briggs et al., 2020).

The U.S. portion of the Chihuahuan Desert serves as an ideal case study for this research due to its significant conservation value, increasing land intensification, and the availability of datasets on ecosystem service values. This ecoregion, the largest desert in North America, covers over 350,000 km^2 in north-central Mexico and the southwestern United States. Although deserts are often perceived as unproductive, they are gaining recognition for their ecological and cultural significance. Notably, the Chihuahuan Desert is one of the most biodiverse deserts globally and is especially critical for endemic cactus species (Jordaan et al., 2021). This region exhibits significant temporal and spatial variability, characterized by fluctuating seasonal and inter-annual rainfall and precipitation patterns. It supports a diverse array of life, including approximately 6,000 plant species, with around 50% being endemic, making it one of the most biodiverse deserts globally. This diversity is reflected in the highly variable carbon flux, which is closely linked to biological activity and vegetation dynamics (Granados-Sanchez et al., 2011). The understanding of seasonal carbon dynamics and the shifting environmental controls in this diverse desert is crucial, as the capacity of terrestrial ecosystems to act as carbon sinks is expected to increasingly rely on these arid, water-limited environments (Flores-Rentería et al., 2023).

The deserts of North America and Mexico host a diverse array of pollinators, including bees, beetles, butterflies and flies. These pollinators are crucial for transferring pollen between plants, which ensures the reproduction and viability of plant species and their offspring. Recent impacts such as overgrazing, severe droughts, and ongoing climate change have transformed this desert from a predominantly grass-dominated ecosystem to one dominated by shrubs. During this transition, forbs, which were once present alongside grasses, have become more dependent on rainfall for successful flowering compared to shrubs (Friggens et al., 2012). This alteration in the landscape has resulted in a dynamic and novel ecosystem for pollinators. The once-prevalent grasses, now

significantly reduced, offer limited foraging resources and produce only small, wind-dispersed pollen (Tryc, 2022). The majority of the ecoregion of Chihuahuan Desert is situated at elevations between 900 and 1500 m, although foothill regions and some isolated mountain ranges in the Meseta Central can exceed 3000 m. According to Schmidt (1979), the climate within this ecoregion is relatively uniform, characterized by hot summers and cool to cold, dry winters. This uniformity arises from several factors: the consistent distance of most areas from moisture sources such as the Gulf of Mexico and the Sea of Cortez, the uniform elevation of the surrounding mountain ranges, and the desert's continental location, which limits frontal precipitation (Bell et al., 2014).

The mountain ranges that traverse the highlands of San Luis Potosí, located in the Chihuahuan Desert of Mexico, serve as crucial refuges for diverse flora and vegetation, with their distribution often restricted to these orographic and climatic "islands". Shrub communities in this area typically fall into categories such as microphyllous, rosetophyllous, and submontane scrub types. Moreover, at higher elevations, small forests of pine, oak, and juniper can be found. Biogeographically, the region is classified within the Mexican Xerophytic region (Chihuahuan Province) and primarily characterized by a Tropical Xeric bioclimate. However, Tropical Desert and Tropical Pluviseasonal bioclimates are also present in some areas (Giménez de Azcárate et al., 2023). Cuatrociénegas, situated in the heart of the Chihuahuan Desert, is historically notable as the birthplace of Mexican President Venustiano Carranza (1917–1920). Economically, the region is recognized for its alfalfa forage production and the cultivation of grapes for both white and red wines. Tourism represents a particularly lucrative sector, largely driven by the area's numerous thermal pools, which are associated with salt deposits primarily composed of sulfates due to high evaporation rates. The city is designated as a "magical town" due to its distinctive culture, architecture, and traditions. This designation highlights its unique symbolism, compelling stories, significant historical events, and charming daily life, all of which contribute to its potential for further economic growth through an expanded tourism industry (Estrada-Castillón et al., 2021).

Desert and semi-desert regions, despite their often-harsh climatic conditions, exhibit significant vegetation diversity. The Chihuahuan Desert is characterized by a predominance of shrubs and grasslands, with notable plant species including *Jatropha dioica*, *Flourensia cernua*, *Turnera diffusa*, *Eucalyptus camaldulensis*, *Euphorbia antisyphilitica*, *Larrea tridentata*, *Lippia graveolens*, *Opuntia*, *Agave*, and *Prosopis*. Many of these endemic plants have applications in food, non-alcoholic and alcoholic beverages, animal feed, fuel, construction, medicine, textile fibers, wax, and ornamental uses. Extensive research has been conducted on these species, focusing on their bioactive compounds, which are recognized for their potential health benefits such as antioxidant, carotenoid, polyphenol, vitamin, and flavonoid content. These compounds have demonstrated positive health effects, including anticancer, antidiabetic, antimicrobial, immune-boosting, anti-inflammatory, cardioprotective, hepatoprotective, neuroprotective, and skin-repairing properties. Moreover, certain bioactive compounds, such as polyphenols and carotenoids, possess antioxidant and antimicrobial properties that are valuable in the food industry. These characteristics suggest potential as natural alternatives to synthetic additives, offering healthier options for food products. While endemic plant species from the Mexican semi-desert hold promise as sources of bioactive ingredients for the food industry, further research is needed to fully utilize these plants and meet the growing consumer demand for healthy, natural foods with nutraceutical benefits (Palomo–Ligas et al., 2022).

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3 Traditional Wild Edibles (WEs) of the Deserts

Reservoir of Ethnomedicine

In recent years, there has been a growing interest in the study of wild edible plant (WEP) resources. However, urbanization and advancements in modern agricultural technology have significantly impacted these resources, leading to their degradation and the erosion of associated traditional knowledge, including that related to indigenous medicine (Pinela et al., 2017). Historically, WEPs have been crucial to human development, particularly during times of famine, serving not only as essential food sources but also as vital medicines (Jia et al., 2022). The collection of wild plants was a fundamental food source for early humans alongside hunting. This practice continued even after the advent of agriculture and animal husbandry. Indigenous communities have preserved traditional knowledge of WEPs as part of their cultural heritage, passing it down orally through generations. The interplay between humans and plants has been recognized as an ecological balance system, vital for maintaining Earth's biodiversity. Ethnobotany, the study of this relationship, seeks to document and analyze the use of local wild plants by ethnic groups for medicinal, nutritional, and economic purposes. In developed countries, particularly in Europe, WEPs are regarded as significant components of ecosystems (Heinrich et al., 2006).

Conversely, in addition to their significance as food sources, modern science is revealing that wild plants play a crucial role in disease resistance. In ancient Arab-Islamic medicine, Al-Razi (865–910 CE) was the first to document the connection between food and medicine. He authored a notable work on the "benefits of foods and the avoidance of their adverse effects", emphasizing the principle that "your medicine is in your food". This suggests that Al-Razi can be considered a pioneer in the fields of health nutrition and nutraceutical science (Al-Fatimi, 2021). The phytochemical composition of many WEPs has been studied with a focus on their nutritional and antioxidant properties, which impact human health and nutrition. Generally, WEPs contain two groups of metabolites: (1) primary metabolites, which are vital for the organism's life, including carbohydrates, fats, proteins, and mineral elements; and (2) secondary metabolites, such as antioxidants primarily in the form of polyphenols and vitamins, which serve to protect the plants. Compared to cultivated food plants, wild food plants (WFPs) are richer and more diverse sources of inorganic metabolites (minerals), contributing to a better balance in human and animal health. The higher mineral content is a key distinguishing factor between wild and cultivated food plants (Sanchez-Bel et al., 2015).

The relationship between food and health is increasingly significant, as consumers seek out foods that are not only healthy but also flavorful and naturally functional. Awareness of these beneficial foods is largely passed down through individual household practices. However, globally, the traditional use of WEPs for both dietary and medicinal purposes is in danger of fading away (Abbasi et al., 2013). Edible wild plants are essential for food and livelihood security for numerous families and communities worldwide. In India, approximately 800 species are used as food sources, primarily by tribal populations. With about 75% of the Indian population residing in rural areas, the consumption of WEs is deeply ingrained in the dietary practices of many

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communities. This practice is closely linked to various aspects of their socio-cultural and spiritual lives and contributes significantly to meeting their nutritional needs. Ethnomedicinal research is crucial for identifying new crude drugs derived from traditionally used medicinal plants. Since the inception of ethnobotany, which has focused on documenting traditional plant-based medicinal knowledge, several key modern pharmaceuticals have been discovered or developed (Ahmed et al., 2014).

The preservation of traditional folk knowledge, the preference for traditional medicine, and the conservation of biodiversity have become increasingly significant to communities, researchers, academics, and policymakers. Ensuring the sustainability of traditional medicinal knowledge, which provides low-cost herbal remedies, necessitates innovative approaches for its preservation within indigenous communities (Yaseen et al., 2018). Sustainable management of rangeland resources depends significantly on the traditional ecological knowledge (TEK) of indigenous peoples with longstanding ties to these areas. Addressing data gaps in desert rangeland monitoring can be enhanced through the integration of advanced scientific techniques. The health and resource availability of extensive rangelands can be assessed using ecological indicators developed by local herders. However, there is a lack of scientific research investigating how community participation and herders' TEK influence rangeland degradation (Asif et al., 2023). WFPs are non-cultivated species utilized for consumption in food-insecure regions, including underdeveloped and developing countries. These plants hold significant economic and medicinal value globally. Pakistan, particularly its desert regions, boasts a diverse array of WFPs. The indigenous populations of these deserts possess extensive traditional knowledge regarding the use and consumption of these vital plants (Shar, 2022).

This chapter basically explores the role of traditional WEs found in desert environments, focusing on their significance as reservoirs of ethnomedicine (Table 3.1). Desert legumes, known for their protein content, play a vital role in human diets, offering a crucial nutritional source in arid regions. Prickly pear is highlighted as an affordable forage crop that enhances food security by providing essential nutrients. The ethnopharmacological status of WEs from the Capparaceae family is examined, revealing their medicinal uses within traditional practices. Additionally, the therapeutic potential of cucurbitaceous WEs is assessed, emphasizing their health benefits. This chapter also

TABLE 3.1
Taxonomic Classification and Life-Form Characteristics of Wild Edible Species

Sr. No.	Wild Edible Species	Family	Common Name	Life Form
1.	*Arthrocnemum macrostachyum* (Moric.) K. Koch	Amaranthaceae	Sea asparagopsis	Shrub
2.	*Oxystelma esculentum* R. Br.	Apocynaceae	Edible oxystelma	Climber
3.	*Carissa carandas* L.		Karanda	Shrub
4.	*Tecomella undulata* (Sm.) Seem	Bignoniaceae	Desert teak	Tree
5.	*Opuntia dillenii* (Ker Gawl.)	Cactaceae	Prickly pear	Cactus
6.	*Opuntia ficus-indica* (L.) Mill		Indian fig opuntia	Cactus
7.	*Opuntia monacantha* (Wild.) Haw.		Flat prickly pear	Cactus
8.	*Capparis decidua* Edgew (Forssk.)	Capparaceae	Desert capers	Shrub
9.	*Capparis spinosa* L.		Common capers	Shrub
10.	*Cleome brachycarpa* Vahl ex DC.		Short-fruited cleome	Herb
11.	*Cressa cretica* L.	Convolvulaceae	Sea purslane	Herb
12.	*Ipomoea batatas* (L.) Lam.		Sweet potato	Herb
13.	*Merremia hederacea* (Burm. fil.) Hall. fil.		Ivy-leaved morning glory	Climber

(Continued)

TABLE 3.1 ***(Continued)***
Taxonomic Classification and Life-Form Characteristics of Wild Edible Species

Sr. No.	Wild Edible Species	Family	Common Name	Life Form
14.	*Citrullus colocynthis* (L.) Schrad.	Cucurbitaceae	Colocynth	Herb
15.	*Cucumis melo* L.		Melon	Herb
16.	*Cucurbita maxima* Duchesne.		Pumpkin	Herb
17.	*Luffa cylindrica* (L.) M. Roem.		Luffa	Herb
18.	*Momordica charantia* L.		Bitter melon	Herb
19.	*Mukia maderaspatana* (L.) M. Roem		Indian kiwifruit	Herb
20.	*Coccinia grandis* (L.) Voigt		Ivy gourd	Herb
21.	*Citrullus lanatus* (Thunb.) Matsum. & Nakai		Watermelon	Herb
22.	*Momordica balsamina* L.		Balsam pear	Herb
23.	*Lagenaria siceraria* (Molina) Standl.		Bottle gourd	Herb
24.	*Acacia jacquemontii* Benth.	Fabaceae	Jacquemont's acacia	Tree
25.	*Acacia nilotica* (L.) Willd. ex Delile		Gum arabic tree	Tree
26.	*Acacia modesta* (Linn.) Wall.		Modest acacia	Tree
27.	*Albizia lebbeck* (L.) Benth.		Lebbeck tree	Tree
28.	*Prosopis cineraria* (Linn.) Druce		Khejri	Tree
29.	*Cyamopsis tetragonoloba* (L.) Taub)		Guar	Herb
30.	*Crotalaria burhia* Buch.-Ham. ex Benth.		Burhia crotalaria	Herb
31.	*Parkinsonia aculeata* L.		Wait-a-minute tree	Tree
32.	*Prosopis juliflora* (Swartz) DC.		Mesquite	Tree
33.	*Tephrosia purpurea* (L.) Pers.		Purple tephrosia	Herb
34	*C. tetragonoloba* (L.) Taub.		Cluster bean	Tree
35.	*Pithecellobium dulce* (Roxb.) Benth.		Madras thorn	Tree
36.	*Bauhinia variegata* L.		Orchid tree	Shrub
37.	*Sesbania bispinosa* (Jacq.) W. Wight		Spiny sesbania	Tree
38.	*Sophora mollis* (Royle) Graham ex Baker		Soft kowhai	Shrub
39.	*Azadirachta indica* A. Juss.	Meliaceae	Neem	Tree
40.	*Broussonetia papyrifera* (L.) L'Hér. ex Vent.	Moraceae	Paper mulberry	Tree
41.	*Ficus palmata* Forssk.		Palm fig	Tree
42.	*Ficus racemosa* L.		Cluster fig	Tree
43.	*Morus nigra* L.		Black mulberry	Tree
44.	*Ficus carica* L.		Common fig	Tree
45.	*Ficus elastica* Roxb. ex Hornem.		Rubber fig	Tree
46.	*Ficus lacor* Buch.-Ham.		Java fig	Tree
47.	*Moringa oleifera* Lam.	Moringaceae	Drumstick tree	Herb
48.	*Nelumbo nucifera* Gaertn.	Nelumbonaceae	Lotus	Shrub
49.	*Peganum harmala* L.	Nitrariaceae	Syrian rue	Herb
50.	*Calligonum polygonoides* L.	Polygonaceae	Knotweed family	Shrub
51.	*Ziziphus nummularia* (Burm. f.) Wight & Arn.	Rhamnaceae	Indian jujube	Tree
52.	*Ziziphus jujuba* Mill.		Chinese jujube	Herb
53.	*Solanum nigrum* L.	Solanaceae	Black nightshade	Herb
54.	*Solanum surattense* Burm. f.		Surattense nightshade	Herb
55.	*Solanum inacnum* L.		Thorn apple	Shrub
56.	*Withania coagulans* (Stocks) Dunal		Indian ginseng	Shrub
57.	*Flacourtia indica* (Burm.)	Salicaceae	Indian flacourtia	Shrub
58.	*Salvadora alii* Rajput & Syeda	Salvadoraceae	Salvadora	Herb
59.	*Fagonia cretica* Linn.	Zygophyllaceae	Cretan fagonia	Herb
60.	*Tribulus terrestris* L.		Puncture vine	Herb
61.	*Viola stocksii* Boiss.	Violaceae	Stocks' violet	Herb

FIGURE 3.1 *Arthrocnemum macrostachyum.*

addresses the nutritional value of drought-resistant rhamnaceous WEs and their biochemical therapeutic applications, particularly those from the Zygophyllaceae family. This comprehensive analysis underscores the importance of these WEs in both nutrition and traditional medicine in desert ecosystems (Figures 3.1–3.36).

FIGURE 3.2 *Azadirachta indica.*

FIGURE 3.3 *Broussonetia papyrifera.*

FIGURE 3.4 *Bauhinia variegate.*

FIGURE 3.5 *Calligonum polygonoidesk.*

FIGURE 3.6 *Citrullus lanatus.*

FIGURE 3.7 *Coccinia grandis.*

FIGURE 3.8 *Carissa carandas.*

FIGURE 3.9 *Cressa cretica.*

FIGURE 3.10 *Ficus palmata.*

FIGURE 3.11 *Ficus racemosa.*

FIGURE 3.12 *Morus nigra.*

FIGURE 3.13 *Ficus carica.*

FIGURE 3.14 *Ficus elastic.*

FIGURE 3.15 *Ficus lacor.*

FIGURE 3.16 *Flacourtia indica.*

FIGURE 3.17 *Ipomoea batatas.*

FIGURE 3.18 *Lagenaria siceraria.*

FIGURE 3.19 *Merremia hederacea.*

FIGURE 3.20 *Momordica balsamina.*

FIGURE 3.21 *Moringa oleifera.*

FIGURE 3.22 *Nelumbo nucifera.*

FIGURE 3.23 *Opuntia ficus-indica.*

FIGURE 3.24 *Opuntia monacantha.*

FIGURE 3.25 *Oxystelma esculentum.*

FIGURE 3.26 *Peganum harmala.*

FIGURE 3.27 *Pithecellobium dulce.*

FIGURE 3.28 *Salvadora alii.*

FIGURE 3.29 *Sesbania bispinosa.*

FIGURE 3.30 *Solanum inacnum.*

FIGURE 3.31 *Solanum nigrum.*

FIGURE 3.32 *Solanum surattense.*

FIGURE 3.33 *Sophora mollis.*

FIGURE 3.34 *Tecomella undulata.*

FIGURE 3.35 *Viola stocksii.*

FIGURE 3.36 *Withania coagulans.*

3.1 DESERT LEGUMES AS A SOURCE OF PROTEIN IN HUMAN DIETS

Recent observations indicate a shift in consumption patterns, with a growing preference for plant-based proteins over animal-based ones, due to the latter's association with an elevated risk of chronic diseases. This change has led to a significant increase in the production of plant-based proteins within the food industry. This is a current trend in dietary protein consumption, comparing traditional animal-based sources with plant-based alternatives, with a particular focus on both conventional and underutilized desert legumes. Proteins play a crucial role in cellular homeostasis, and this review highlights the potential risks associated with long-term consumption of animal proteins. It discusses the increasing appeal of plant-based proteins, especially those derived from legumes, as a viable solution to global malnutrition issues. The nutritional value of legume-based proteins and bioactive peptides is analyzed, emphasizing their significance. Moreover, underutilized desert legumes are explored as sustainable protein sources with potential health benefits and industrial applications, such as in the production of plant-based cheese and meat. Plant proteins often exhibit lower digestibility due to physical barriers such as cell walls and complex macromolecules, including cellulose, pectin, mucilaginous carbohydrates, and xylem (Chauhan et al., 2024).

Leguminosae (Fabaceae) species are valuable plant-based sources of essential nutrients and proteins, particularly in regions with limited access to animal protein sources (Henchion et al., 2017). This family comprises approximately 750 genera and 19,000 species (Putra et al., 2022). Legumes contribute 33% of the global protein supply for medicine, food, fodder, and shelter. They offer significant benefits as both nutraceuticals and protein sources, addressing malnutrition issues characterized by under-nutrition, which leads to hunger and stunted growth, and over-nutrition, which contributes to chronic conditions such as obesity. Regular legume consumption can help mitigate these nutritional extremes and promote overall health. Furthermore, legumes have the lowest greenhouse gas (GHG) footprint among protein sources (Clune et al., 2017).

As the impact of climate change intensifies, traditional food crops like rice are increasingly vulnerable to heat stress, leading to reduced yields and heightened disease risks. This scenario necessitates the exploration of alternative food sources, particularly those derived from indigenous plants that are more resilient and require less water and fewer chemical inputs. In the arid and semi-arid desert regions of the world, there are wild plants that could serve as valuable alternatives. These plants not only offer potential as functional foods providing essential carbohydrates, proteins, and micronutrients but also possess health-promoting properties through bioactive compounds like antioxidant flavonoids and beneficial enzymes (Joshi et al., 2024). Furthermore, various non-edible parts of these plants have been validated through traditional ethnomedicinal practices and could serve as sources of bioenergy. The adoption of underutilized legumes is crucial for enhancing food security, especially in the context of climate change. These legumes are rich in nutrients, improve soil fertility, and can help mitigate the impact of climate change. Their resilience to adverse climate effects such as erosion and disease further supports their role in maintaining food security. Additionally, underutilized legumes can aid in controlling plant diseases and weeds. They are cost-effective and provide high protein content, which is essential for health, particularly when animal protein sources are being reconsidered due to health concerns (Ayilara et al., 2022).

Legumes are a primary source of dietary protein. Ideally, a protein source should provide all nine essential amino acids, which are typically more abundant in animal-based proteins. However, consumption of meat has been linked to an increased risk of diet-related non-communicable diseases, such as colorectal cancer, diabetes mellitus, and coronary heart disease. Since no single legume contains all nine essential amino acids, it is beneficial to complement commonly consumed legumes with underutilized varieties in a mixed diet. This approach aims to address potential amino acid deficiencies through a diverse legume combination. Achieving this goal requires scientists to explore and thoroughly characterize both the nutritional and nutraceutical potential of underutilized legumes (Chung et al. 2021).

Acacia jacquemontii, *Acacia nilotica*, *Acacia modesta*, *Albizia lebbeck*, *Prosopis cineraria*, *C. tetragonoloba*, *Crotalaria burhia, Parkinsonia aculeata*, *Prosopis juliflora*, and *Tephrosia purpurea* are some of the underutilized edible legumes found in desert lands. These legumes have potential for use as sources of bioactive compounds and bioenergy. Specifically, *P. cineraria* and *A. senegal* are commonly used in traditional dishes, exemplifying how local populations leverage available resources to meet nutritional needs while employing various methods for conservation and sustainability (Singh et al., 2023a). This chapter also discusses the cultural knowledge and regional and seasonal availability of these plants, highlighting opportunities for their innovative utilization.

3.1.1 *A. Jacquemontii* Benth.

A. jacquemontii, commonly known as Bable or Kikri, is a highly valuable multi-use shrub adapted to the harsh conditions of arid and semi-arid desert rangelands (Figure 3.37; Table 3.2). Its resilience to extreme climates makes it an exceptional resource for fuel, forage, gum, tannin, and small poles, in addition to having various medicinal applications for both livestock and humans (Singh et al., 2003). This shrub naturally occurs in patches on sand dunes and interdunal sandy plains, with greater frequency and density observed on bare, undulating sand dunes. Although it is a relatively underutilized species, *A. jacquemontii* holds significant potential as a multipurpose shrub. Its leaves and pods are rich in highly digestible proteins and essential minerals, making them valuable for feeding sheep and goats in parts of South Asia (Rasool et al., 2017). *A. jacquemontii*, a drought-resistant leguminous plant native to arid desert regions, offers a viable protein source for human diets in such environments due to its adaptive features and nutritional profile. This species

FIGURE 3.37 *Acacia jacquemontii.*

TABLE 3.2
Detailed Aspects of *Acacia jacquemontii* as a Source of Protein in Human Diets

Aspects	Details	Nutritional Value	Health Benefits	Cultivation
Protein Content	Approximately 15–20% protein content in seeds	15–20% protein (in seeds)	Supports muscle growth, repair, and overall health	Grows in arid and semi-arid regions
Amino Acid Profile	Contains essential amino acids such as lysine, leucine, isoleucine, and valine	Essential amino acids present	Contributes to balanced diet; aids in protein synthesis and metabolic processes	Prefers well-drained soils, tolerant to drought
Carbohydrates	High in carbohydrates, including dietary fibers	High carbohydrate content	Provides energy and supports digestive health	Requires minimal irrigation once established
Fats	Low in fats Primarily unsaturated fatty acids	Low fat content	May contribute to heart health and reduce cholesterol levels	Can be grown in sandy or rocky soils
Vitamins	Contains vitamins such as vitamin A, vitamin C, and B vitamins	Vitamins A, C, and B complex present	Supports immune function, skin health, and overall well-being	Thrives in temperatures ranging from 20°C to 35°C
Minerals	Rich in minerals such as calcium, potassium, magnesium, and iron	High in calcium, potassium, magnesium, and iron	Enhances bone health, supports cardiovascular function, and helps in various metabolic processes	Requires minimal maintenance, suited for dry climates
Antioxidant Content	Contains polyphenols, flavonoids, and other antioxidants	Rich in polyphenols and flavonoids	Provides antioxidant protection, reduces oxidative stress, and may help in disease prevention	Can be used in agroforestry systems and soil erosion process

can thrive under extreme conditions, providing a stable source of plant-based protein essential for human nutrition. Its seeds are rich in protein, fiber, and essential amino acids, which can be harnessed to address dietary deficiencies in regions with limited agricultural resources. The plant's ability to fix nitrogen enhances soil fertility, further supporting its cultivation in nutrient-poor desert soils. Furthermore, the resilience of *A. jacquemontii* to harsh climates ensures a consistent supply of protein, contributing to food security and sustainability in arid regions.

A. jacquemontii feature small, wax-coated leaves that minimize transpiration, enabling the shrub to endure arid conditions effectively. The shrub's extensive taproots can penetrate deep into the ground, accessing subterranean water sources. This adaptation allows the plant to sustain its vitality and remain green even during periods of water scarcity in dry environments (Rasool et al., 2016). The production of above-ground biomass in *A. jacquemontii* is influenced by site, habitat, and climatic conditions. Plants growing in deep soils typically produce the highest amounts of above-ground biomass compared to those growing in shallow soils (Kunhamu et al., 2005). In addition to its gum, *A. jacquemontii* provides valuable products such as fodder, fruits, and fibers. Traditionally, a decoction of the plant's bark has been used to treat fever, muscle pain, and cough, with in vivo studies confirming its analgesic, anti-inflammatory, and antipyretic properties (Ashfaq et al., 2016). The gum from this plant is utilized as a health tonic in various food products and is beneficial for individuals recovering from serious injuries or childbirth. The gum's demulcent and astringent properties make it a common component in medicinal preparations. For asthma treatment, the gum

is heated and administered daily for one month, and it is also used to alleviate mouth ulcers (Ahmed et al., 2022). The bark of *A. jacquemontii* is traditionally used to induce spontaneous abortion at any stage of pregnancy. The treatment involves boiling 100 grams of fresh bark from older trees in one glass of water until only one-quarter of the liquid remains. The decoction is then strained, cooled, and consumed. The standard protocol is to administer three doses per day over a three-day period. This treatment is typically used only when there is suspicion of fetal malformation or premature rupture of the amniotic sac (Choudhary et al., 2009a).

Awan et al. (2022) explored the therapeutic potential of *A. jacquemontii* ethyl acetate extract (AJEAE) in managing hyperglycemia through a comprehensive study involving both in vitro and in vivo analyses. The study aimed to assess AJEAE's impact on hyperglycemia by evaluating its effects on various biochemical and physiological parameters. AJEAE contains several active compounds, including quercetin, kaempferol, and various acids such as gallic and vanillic. The extract demonstrated significant antioxidant activity with a 69.47% inhibition rate in the DPPH (2,2-diphenyl-1-picrylhydrazyl) assay and a 71.8% α-amylase inhibition rate. Diabetic rats exhibited significant hyperglycemia, hypoinsulinemia, elevated triglycerides, cholesterol, and inflammatory markers, along with decreased high-density lipoprotein and antioxidant enzyme levels. Treatment with AJEAE significantly improved these parameters, showing efficacy comparable to glibenclamide. Histopathological examinations further supported AJEAE's anti-hyperglycemic effects by indicating pancreatic β-cell regeneration.

Mahmood et al. (2023) investigated the effectiveness of cobalt oxide nanoparticles (Co3O4 Nbs) in mitigating lead (Pb) toxicity in *A. jacquemontii*, a species adversely affected by soil contamination. The study applied Co_3O_4 NPs (nanoparticles) at varying concentrations and found that the 75 ppm concentration yielded the most significant improvements. Notable enhancements in plant growth were observed, including a 39% increase in root length, 32% in fresh weight, 58% in shoot length, and 28% in dry weight compared to the control. Thus, Co_3O_4 NPs offer a promising nanotechnological approach to counteracting lead-induced soil toxicity, thereby supporting the growth and health of *A. jacquemontii* and potentially enhancing agronomic management strategies.

A. jacquemontii, a thorny xerophytic shrub endemic to the arid and semi-arid Thar Desert, is crucial for soil stabilization and fertility enhancement due to its deep root system, nitrogen-fixing ability, and role in preventing soil erosion (Ragupathy et al., 2014). Its leaves serve as fodder for livestock, while its bark has medicinal uses. Despite previous reports on the nodulation of native legumes in alkaline soils of the Thar Desert, there is limited understanding of the specific rhizobia associated with native acacias. The present study aimed to assess the genetic diversity of rhizobia nodulating *A. jacquemontii* by characterizing their core, 'housekeeping', and symbiotic genes, as well as determining their host range to better understand their ecological contributions to this fragile ecosystem (Sankhla et al., 2017).

A. jacquemontii, widely distributed across semi-arid regions, is a multifunctional tree ideal for afforestation, social, and agroforestry applications. Beyond its conventional uses in wood production, soil enhancement, and nitrogen fixation, it also yields various products including fodder, fruits, gums, fibers, and roofing materials. The bark is utilized as inoculum for fermentation and local spirits, while the dried gum from the stem, known for its demulcent properties, is often included in medicinal preparations. Additionally, the powdered bark has traditional uses for inducing spontaneous abortion, treating snake bites, and in various ethnomedicinal applications (Al-Mosawi & Thevenet, 2006). The ethanolic extract of the stem bark has demonstrated antimicrobial activity against a range of pathogens such as *Bacillus cereus*, *Bacillus pumilus, Escherichia coli*, *Pseudomonas aeruginosa*, *Staphylococcus aureus*, *Staphylococcus pyogenes*, and *Candida albicans*. Active principles in the extract include terpenoids, tannins, alkaloids, saponins, and glycosides. This study highlights *A. jacquemontii*'s potential antimicrobial properties, suggesting the need for further toxicological studies, purification of active compounds, and broader testing against additional bacteria and fungi (Choudhary et al., 2009b).

Sharif et al. (2020) investigated the traditional use of *A. jacquemontii* for treating hypertension by evaluating the antihypertensive effects of its crude extract and various fractions in anesthetized rats. The study involved administering different doses of the crude extract and fractions (hexane, ethyl acetate, n-butanol, aqueous). Various pharmacological inhibitors were used to explore the mechanisms of action, including L-NAME, atropine, captopril, propranolol, and hexamethonium. AJB demonstrated significant dose-dependent reductions in systolic blood pressure, diastolic blood pressure, and mean arterial pressure in both normotensive and hypertensive rats, with notable effects at $p<0.05$ to $p<0.001$. AJB's hypotensive action was mediated through β-receptors, ganglionic blockade affecting central sympathetic neural responses, and modulation of the renin-angiotensin-aldosterone system.

Muhammad et al. (2021) found that the canopy cover of *A. jacquemontii* significantly affects soil characteristics, with soils under the canopy exhibiting higher levels of organic matter, nitrogen, phosphorus, and potassium compared to barren soils, indicating greater fertility. The study also revealed that the mineral composition of the soil is positively influenced by the presence of canopy cover. The expanding plantation of *A. jacquemontii* in the Thal Desert is recommended as it could enhance soil quality, making the land more suitable for cultivation. This improvement has the potential to alleviate local financial difficulties and positively impact the national economy.

In the study by Awan et al. (2024), the therapeutic potential of polyphenols from *A. jacquemontii* was investigated through both in vitro and in vivo experiments. The in vitro analysis involved the characterization of AJ extracts using high-performance liquid chromatography (HPLC) and demonstrated significant antioxidant, antidiabetic, and anti-inflammatory activities. Specifically, A.J. extracts were found to contain notable levels of flavonoids and phenolic acids, with potent antioxidant effects, including high radical scavenging and FRAP activities. The extracts exhibited considerable inhibition of α-glucosidase, DPP-IV, LOX, and HYA enzymes. In vivo studies with Wistar rats showed that both AJ n-hexane extract (AJHE) and AJ methanol extract (AJME) at 250 mg/kg improved glycemic indicators compared to diabetic controls, with significant enhancements in plasma insulin, HOMA-β, and serum C-peptide levels. Additionally, AJ extracts contributed to the normalization of carbohydrate-metabolizing enzyme levels and promoted β-cell regeneration in the pancreas. The study suggests that the polyphenolic compounds in AJ are likely key contributors to its effects on glucosidase, DPP-IV, LOX, and HYA inhibition, as well as the regulation of glucose homeostasis.

3.1.2 *Acacia nilotica* (L.) Willd. ex Delile

A. nilotica, commonly known as babul, is a significant ornamental and medicinal plant native to tropical and subtropical desert regions (Figure 3.38). It belongs to the Fabaceae family and the Acacia genus. This plant is a rich source of various active secondary metabolites, which have substantial potential as candidates for future drug development. In various countries, *A. nilotica* has been introduced for uses such as fuel wood, forage, and notably as a medicinal plant. This species is a rich source of polyphenols, including condensed tannins, phlobatannins, gallic acid, ellagic acid, catechin, and epigallocatechin-7-gallate. In traditional medicine, every part of the plant is valued for its therapeutic properties and has been used to treat a range of diseases and ailments worldwide. Recently, *A. nilotica* has been studied for its diverse biological activities, such as antidiabetic, hypolipidemic, and antileishmanial effects; reduction of plasmodial infection pathogenicity; and molluscicidal properties (Rather & Mohammad, 2015). The plant *A. nilotica* is highly significant due to its substantial nutritive and therapeutic values. It has been introduced in various countries as forage, fuel wood, and importantly as a medicinal plant. The presence of numerous bioactive compounds enhances its value across different medical systems. Every part of *A. nilotica*, including the bark, gum, fruits, seeds, leaves, roots, and flowers, contains therapeutic compounds and nutrients beneficial for treating and preventing a range of diseases and disorders. These include conditions such as coughs, colds, cancer, typhoid, hemorrhage, fever, intestinal pain, and diarrhea, among others.

FIGURE 3.38 *Acacia nilotica.*

A. nilotica is a pioneering species known for its high content of bioactive secondary compounds and its economic value, being used for tannins, gums, timber, fuel, and fodder. The concentrations of potassium, iron, zinc, copper, and manganese in *A. nilotica* seeds were found to be 2.1, 203.1, 108.7, 322.7, and 1.09 g/100g dry weight, respectively. The seed's oil, crude protein, and crude fiber contents were measured at 4.1%, 25.3%, and 28.4%, respectively, based on fresh weight. This study highlights that mature seeds of *A. nilotica*, native to southern Iran, are particularly rich in mineral elements, especially iron and potassium (Abbasian et al., 2015). The nutritional and antinutritional characteristics of *A. nilotica* (L.) Del. seeds were evaluated, revealing that mature seeds contain 234 g/kg crude protein, 126 g/kg crude fiber, 66.6 g/kg crude fat, 39.7 g/kg ash, and 534 g/kg carbohydrates. Key minerals such as potassium, phosphorus, magnesium, iron, and manganese were present in high concentrations. The essential amino acid profile was mostly aligned with FAO/WHO recommendations, though cystine, methionine, and threonine were identified as limiting amino acids. Compared to the globulin fraction, albumins were richer in cystine, methionine, threonine, lysine, and tryptophan. Oleic and linoleic acids were the primary fatty acids, making up 66.9% of the total. Processing methods like dry-heating and autoclaving significantly reduced antinutritional factors, with in vitro protein digestibility improving from 61.2% in raw seeds to 77.4% with dry heat treatment and 80.2% with autoclaving. Processed seeds demonstrated significantly higher biological value, true digestibility, and net protein utilization compared to raw seeds, though the difference in usable protein between raw and processed seeds was minimal (Siddhuraju et al., 1996).

In traditional medicine, *A. nilotica* is valued for its rich nutrient content and therapeutic compounds, which are believed to prevent, alleviate, and treat a variety of infectious diseases and health conditions. Ayurvedic practices recommend using the leaves, bark, and pods of *A. nilotica* for ailments such as cancer, coughs, diarrhea, fever, smallpox, hemorrhoids, and menstrual issues. The bark and pods have also been shown to inhibit the hepatitis C virus. Plant extracts from *A. nilotica*,

which are high in bioactive compounds and antioxidants, have potential applications in food, agriculture, nutraceuticals, cosmetics, and pharmaceuticals. These secondary metabolites could provide an alternative strategy for combating drug-resistant infections, either alone or in combination with antibiotics (Sadiq et al., 2015). Over 900 species of *Acacia* trees exist globally, many of which produce gums. *A. nilotica*, commonly known as the Babul tree, is a significant gum-yielding species native to the Indian subcontinent. Acacia gum, derived from this species, has been extensively researched and utilized commercially due to its low viscosity at higher concentrations, superior water solubility, and effective emulsion properties (Bhushette & Annapure, 2017). The *A. nilotica* tree exhibits a broad tolerance for varying rainfall levels and can endure temperatures up to 50°C. Its robust tap root system allows it to efficiently access nutrients and moisture throughout the soil column. This tree is relatively fast-growing, drought-resistant, and possesses the capability to fix nitrogen, with reports indicating it forms nodules with rapidly growing rhizobium strains (Choudhary et al., 2020). Plants are crucial to human life, fulfilling essential needs and serving as a source of medicine since ancient times. Globally, many people depend on phytomedicine for primary healthcare, leading to a growing demand for plant-based treatments. *A. nilotica*, a perennial tree, is renowned for its therapeutic potential and has been used in folk medicine for centuries. The entire plant is rich in carbohydrates, lipids, proteins, vitamins, minerals, and secondary metabolites. This review provides a comprehensive update on the morphology, phytochemistry, and therapeutic potential of *A. nilotica*, along with other relevant information (Janani & Ahamed, 2020). In a recent survey, it is observed that a 2:1 (v/v) phytococtail of *A. nilotica* leaf extracts is consumed in a fasting state during early mornings by local tribes in certain regions of Bengal, India. This practice is followed for a duration of 3–4 months as a traditional remedy for managing diabetic complications (Saha et al., 2018).

A. nilotica is a significant species that offers fuel wood, forage, and enhances soil fertility in the arid and semi-arid regions of India. This species is capable of thriving in highly saline environments, alkaline soils, coastal areas, desert sand dunes, river ravines, and degraded dry grasslands. The drought-resistant shrubs of *A. nilotica* are valued for their roles in sand stabilization, soil binding, creating living fences, producing charcoal, providing hard timber, and serving as quality animal feed (Baka, 2014). The optimization parameters affect oil yield from *A. nilotica* using solvent extraction. *A. nilotica*, a non-edible feedstock often referred to as the 'miracle plant', is prevalent in arid and semi-arid regions. Soxhlet extraction was used to obtain oil from *A. nilotica*, with n-Hexane as the solvent at solid-to-solvent ratios of 3:1, 5:1, and 7:1 (v/w) and extraction times of four, five, and six hours, within a temperature range of 60°C–70°C. Optimization was performed using response surface methodology (RSM) with Design Expert version 7.1.5 and D-optimal design, focusing on solvent-to-seed ratio, reaction temperature, and extraction time. This approach facilitates the conversion of non-edible *A. nilotica* into biodiesel, addressing the food versus fuel debate (Rajeshwaran et al., 2020). *A. nilotica* can inhibit bacterial growth by precipitating bacterial proteins, leading to a depletion of essential nutritional proteins. It can also form irreversible complexes with proline-rich proteins within bacterial cells, thereby halting protein synthesis. The pods of *A. nilotica* are notably rich in proteins and essential amino acids and are also abundant in various organic compounds and phytochemicals, including alkaloids, phenols, resins, steroids, oleosins, phenolics, glycosides, tannins, and volatile essential oils. The desert climate can induce distinct biochemical and physiological responses, affecting plant growth, development, and the production of metabolites, particularly natural antioxidants (mainly phenolic compounds), hydrocarbons, and terpenoids (Alduraihem et al., 2023).

3.1.3 *Acacia modesta* (Linn.) Wall.

A. modesta (Mimosaceae), a leguminous shrub native to arid regions, shows promise as a sustainable forage resource due to its high protein content and adaptability to desert environments (Figure 3.39). This species is known for its robust tolerance for drought and poor soil conditions,

FIGURE 3.39 *Acacia modesta.*

making it a viable candidate for enhancing the nutritional quality of human diets in arid areas. The seeds of *A. modesta* are rich in essential amino acids, vitamins, and minerals, which can contribute to improved dietary diversity and nutritional intake in regions where conventional crops are less viable. Moreover, the plant's nitrogen-fixing abilities enhance soil fertility, promoting a more resilient agricultural system. However, further research is needed to optimize its cultivation practices and fully understand its nutritional benefits and potential anti-nutritional factors.

A. modesta is garnering increasing interest for its potential inclusion in sustainable cultivation and harvesting programs. This medicinal and aromatic tree, prevalent in Dargai, is valued by beekeepers who use its branches in apiculture. Traditionally, various preparations of *A. modesta* have been employed in local medicine to treat a range of conditions, including musculoskeletal issues, postnatal back pain, chronic stomach disorders, and dysentery (Sher et al., 2012). The plant's branches also serve as toothbrushes. *A. modesta* offers economic benefits; it is utilized as wood fuel, in construction, as fodder, for timber, and for fencing, and plays a role in beekeeping (Murad et al., 2011). The extract from *A. modesta* leaves has demonstrated in vivo anti-hyperglycemic effects in alloxan-induced diabetic rats (Saleem et al., 2018). Methanolic extracts of the leaves exhibit analgesic, anti-platelet, and anti-inflammatory activities, with its antioxidant potential validated through various assays including DPPH scavenging, hydrogen peroxide scavenging, superoxide radical scavenging, and ABTS (2,2′-azino-bis(3-ethylbenzothiazoline-6-sulfonic acid) scavenging activities. Furthermore, the bark extracts of *A. modesta* have shown hepatoprotective properties, as evidenced by the analysis of serum levels of hepatic metabolic enzymes and plasma proteins to assess hepatotoxicity (Chaudhry, 2015). *A. modesta* is traditionally used to treat leprosy, wounds, dysentery, and venereal diseases. The ash from A. *modesta* wood has been utilized for alleviating severe body pain. A mixture of gum with wheat flour,

almonds, and butter was administered to women post-delivery, while Zhuble sharbat, a solution of gum in water, served as a health tonic. The antimicrobial properties of *A. modesta* led to its branches being used as miswaks (toothbrushes). The gum has also been employed for its curative effects on back pain and sexual health, and the plant has been utilized in the treatment of coughs (Sarwar, 2016). Various parts of *A. modesta* are used for multiple therapeutic purposes, including dental hygiene, wound care, treatment of venereal diseases, trachoma, oral toothache, leprosy, and dysentery (Abid et al., 2020, 2021). An extract of *A. modesta* has demonstrated efficacy against *Lactobacillus* (a gram-positive bacterium) as reported by Mahmood and Hassan (2003). In studies, normal rats that were fed a diet incorporating powdered seeds from *A. modesta* and other *Acacia* species showed lower blood sugar levels compared to rats that were given a standard semi-purified diet consisting of casein, glucose, and starch (Ahmad et al., 2012b). *A. modesta* has a traditional use in treating rheumatic disorders within herbal medicine. The continued reliance on traditional remedies is due to the significant side effects associated with commercial pharmaceuticals. Gas chromatography-mass spectrometry (GC-MS) analysis of *A. modesta* has identified phytochemicals with known anti-inflammatory and antioxidant properties, which may contribute to its antiarthritic effects. Notably, lupeol, a potent anti-inflammatory and antioxidant compound, mitigates arthritis progression by inhibiting the PI3K/Akt signaling pathway (Mashaal et al., 2023).

It is demonstrated that *A. modesta* exhibits significant antibacterial activity against pathogens like *Bacillus subtilis*, *Salmonella spp.*, *Escherichia coli*, and *Vibrio cholera*, as well as notable antioxidant properties through free radical scavenging. However, the slow growth rate of *A. modesta* poses challenges for its widespread use and conservation, raising concerns about over-exploitation and potential endangerment. In light of this, our study focused on overcoming these limitations by utilizing callus culture techniques. Callus was successfully induced from axillary buds using MS medium enriched with 2,4-D and BAP. Analysis of the callus extract revealed elevated levels of phenolics, flavonoids, and volatile compounds, alongside enhanced antibacterial and antioxidant activities compared to the leaf extract of the parent plant. Thus, callus culture presents a viable alternative for the large-scale production of valuable secondary metabolites from *A. modesta*, mitigating issues related to slow growth and over-harvesting (Hagaggi et al., 2024).

Gum from *A. modesta* has been extensively analyzed for its macromolecular structure and monosaccharide composition. This gum is characterized as a highly branched polysaccharide primarily consisting of galactose and arabinose, with smaller amounts of rhamnose and other monosaccharides. Notably, *A. modesta* gum contains relatively low levels of α-l-arabinofuranose, with β-d-galactopyranosyl linked predominantly through 1,3-linkages being the major component. The polysaccharide chains include structural motifs such as α-l-Araf-(1 → 4)-β-d-Galp, α-d-Galp-(1 → 3)-α-l-Araf, and β-d-Galp-(1 → 6)-αβ-d-Galp. Additionally, the gum contains a significant fraction (>2%) of polypeptides, as well as notable quantities of flavonoids and alkaloids (Irfan et al., 2022). The gum from *A. modesta* is utilized across various industries, including pharmaceuticals, textiles, food, and cosmetics, where it serves as a stabilizing, binding, and emulsifying agent. Analysis of its macromolecular structure using nuclear magnetic resonance (NMR) and Fourier transform infrared spectroscopy (FT-IR) has revealed that it is composed of complex polysaccharides, featuring both reducing and non-reducing carbohydrates. The primary sugars in the gum are arabinose and galactose, with rhamnose present in smaller quantities. This gum is classified as a heteropolysaccharide due to its significant content of hydroxyproline-rich proteins (Irfan et al., 2023). Chemical investigation of the butanol fraction from the non-flowering aerial parts of *A. modesta* resulted in the identification of three compounds. Based on chromatographic properties, Compound 1 was anticipated to be an apigenin derivative. This was confirmed through analysis of its ^{1}H NMR and ^{13}C NMR spectra, which exhibited characteristic signals corresponding to the apigenin aglycone moieties, thereby validating its identity as vitexin-2″-β-glucopyranoside (Salah et al., 2020).

3.1.4 *Albizia lebbeck* (L.) Benth.

A. lebbeck, commonly known as the Indian siris tree, is a leguminous species well-suited to desert environments, offering significant potential for enhancing human nutrition and food security in arid regions (Figure 3.40). This hardy species thrives in harsh desert conditions, characterized by low water availability and extreme temperatures, making it a valuable resource for sustainable agricultural practices. The tree produces nutrient-rich seeds and leaves that can be utilized as a dietary supplement, providing essential proteins, vitamins, and minerals. Its adaptability to desert conditions and nutritional benefits position *A. lebbeck* as a critical component in strategies aimed at improving food security and supporting human health in arid and semi-arid areas. Originating from Asia, *A. lebbeck* has been introduced to various regions worldwide. This species is recognized for its high potential in erosion control and is utilized for forage and firewood. It functions as a nitrogen-fixing tree and exhibits a high photosynthetic rate (Mukhopadhyay & Masto, 2022).

A. lebbeck, a versatile tree native to tropical and subtropical regions, is increasingly recognized for its potential as a food resource in desert environments. Its leaves, seeds, and pods are valuable sources of protein, fiber, and essential nutrients, making them particularly useful in arid areas where traditional crops struggle to thrive. The tree's adaptability to harsh conditions and its ability to improve soil fertility through nitrogen fixation further enhance its role in sustainable food systems in desert regions (Ekun, 2022; Mokat & Kharat, 2023). Given its nutritional benefits and ecological contributions, *A. lebbeck* holds promise as a resilient and valuable plant for combating food insecurity in arid climates.

FIGURE 3.40 *Albizia lebbeck.*

A. lebbeck belonging to the Fabaceae family is known by various names, including Siris and Shiris in Hindi, Lebbeck tree in English, and Bhandi, Sitapuspa, Sukapriya, and Mrdupuspa in Sanskrit. Predominantly found in tropical and subtropical regions of India, Andaman Islands, Myanmar, tropical Africa, Asia, and northern Australia, this plant has garnered significant interest due to its diverse phytochemical profile and notable medicinal properties. Traditionally, it has been used for its anti-asthmatic, anti-inflammatory, anti-fertility, anti-diarrhea, antiseptic, anti-dysenteric, and antitubercular effects. Moreover, it treats ringworms, wounds, gonorrhea, leucorrhea, bronchitis, leprosy, paralysis, helminth infections, and other genital diseases. Key phytoconstituents such as melacacidin, D-catechin, β-sitosterol, albiziahexoside, betulnic acid, and echinocystic acid glycosides contribute to its varied physiological and pharmacological activities (Verma et al., 2013). *A. lebbeck* is a deciduous tree with significant medicinal applications across a range of health conditions. It is used to address disorders related to the respiratory system, skin, gastrointestinal tract, oral health, eyes, urinary system, genital area, and anorectal region, as well as inflammatory, neurological, and venereal diseases. This species is renowned for its remarkable therapeutic properties and is employed globally to address a diverse array of diseases and ailments. Traditionally, the plant has been utilized in the treatment of conditions such as ulcers, night blindness, respiratory disorders, skin diseases, snake bites, hemorrhoids, and leprosy. In Indian traditional medicine, all parts of the plant – root, leaves, flowers, bark, and seeds – are utilized to address a range of health conditions. These include allergies, asthma, bronchitis, arthritis, fractures, gingivitis, gum inflammation, toothache, hemorrhage, leprosy, leukoderma, malaria, night blindness, scorpion stings, snakebites, and syphilis (Balkrishna et al., 2022). *A. lebbeck* is utilized in Ayurveda to prepare a range of medicinal formulations. Extracts from its bark, leaves, seeds, and fruits are recognized for their phytochemical content, which helps neutralize body toxins and treat allergies, diarrhea, and inflammation. Additionally, the tree is cultivated for its use as fodder, firewood, and construction material, and is also a valuable source of charcoal. The dried seed pods have low moisture content, making them ideal for biomass conversion via pyrolysis (Rajamohan et al., 2023).

A. lebbeck leaves, known for their high flavonoid content, exhibit antitumor effects against HepG2 hepatoma cells. Zinc oxide nanoparticles synthesized from plant stem bark show cytotoxicity against both highly and weakly metastatic human breast cancer (BCa) cells. Quercetin, a flavonoid present in *A. lebbeck*, is non-toxic and possesses various biological activities, including anticancer, anti-inflammatory, and antioxidant properties (Umar et al., 2023). The plant is cultivated as an ornamental tree for its fragrant flowers and attractive appearance. It helps control soil erosion due to its root structure, which stabilizes the soil. The wood is utilized as fuel, while the leaves serve as fodder, containing 17–26% crude protein. From 100 kg of leaves, 11–12 kg of digestible protein and 37 kg of digestible carbohydrates can be obtained. This woody legume exhibits nitrogen-fixing activity, which increases as the plant matures. The seeds of the plant are rich in protein and crude fiber and contain saponins as well as minerals such as magnesium, iron, and selenium. After appropriate processing to eliminate anti-nutritional factors, the seeds can be utilized as fodder (Waseem et al., 2020). The plant has a high capacity for accumulating heavy metals, making it an excellent candidate for phytoremediation. It is adaptable to a wide range of environmental conditions (Naveed et al., 2023).

The exploration of new sources of protein to address widespread malnutrition, researchers investigated using the leaves of the *A. lebbeck* tree as a protein-rich dietary supplement. They developed a method to extract protein concentrate from the leaves and tested it on leaves from different parts of the tree (lower, middle, and upper canopies). The extraction process was fine-tuned to use a specific ratio of leaves to water and involved heating and acid treatment to separate the protein. The process yielded protein concentrates with protein content ranging from 37.15% to 37.76%, with similar yields across different parts of the tree (about 6% of the leaf weight). The researchers also assessed the nutritional value of these protein concentrates, including their vitamins, minerals, digestibility, and potential anti-nutritional factors. The analysis showed that the protein concentrates from different parts of the tree were quite similar in terms of nutritional

quality (Khan & Varshney, 2018). The examination of water-soluble polysaccharides extracted from *A. lebbeck* seeds are known to be rich in such compounds. Given the pods' composition – containing 36.4% cellulose, 8.9% hemicellulose, 3.6% lignin, and 83.1% volatile matter (Ahmed & Theydan, 2014), the focus is on characterizing the polysaccharides in terms of their structure, functionality, and morphology. Moreover, the research evaluates the potential of these polysaccharides for use in tablet formulation and assesses their drug release profiles, aiming to determine their suitability for pharmaceutical applications (Varma & Kumar, 2017).

3.1.5 *Prosopis cineraria* (Linn.) Druce

P. cineraria, commonly known as the "Screwbean Mesquite" or "Ghaf tree," is a resilient desert legume renowned for its exceptional adaptability to arid environments (Figure 3.41). *P. cineraria* thrives in extreme conditions, contributing significantly to soil stabilization and biodiversity. Its potential as a sustainable food source is gaining attention due to its nutrient-dense seeds and pods, which are rich in protein, dietary fiber, and essential minerals. This adaptability and nutritional value make *P. cineraria* a promising candidate for enhancing food security and nutritional sustainability in arid and semi-arid regions. By leveraging its capabilities, we can address challenges related to food scarcity and environmental sustainability, making it a valuable asset in the quest for sustainable agricultural practices and food systems. *P. cineraria*, a long-lived phreatophyte, develops an extensive tap root system that can extend over 30 meters to access subterranean water sources. This species exhibits both drought and salinity tolerance and can endure extreme temperature fluctuations, ranging from over 45 °C to below 10 °C, typical of desert environments. Notably, *P. cineraria* has a unique flowering adaptation, blooming during the hot, arid season when water availability is limited (Sudalaimuthuasari et al., 2022). *P. cineraria* is indigenous to the dry and arid regions of Arabia and India, with its primary populations concentrated in the Thar Desert spanning India and Pakistan. Less extensive populations are found in the Arabian Peninsula, Iran, and

FIGURE 3.41 *Prosopis cineraria.*

Afghanistan. Recognized as the national tree of the United Arab Emirates, *P. cineraria* is known by various names: "Ghaf" in Arabic, "Khejri" in India, and "Jand" in Pakistan.

Recent studies explained the significant impact of *P. cineraria* on agricultural economies and rural development. This species, while sharing many characteristics with other *Prosopis* varieties such as chemical composition, phytochemical profiles, and health benefits, stands out for its extensive utility. Valued across various cultures for its multifaceted uses, *P. cineraria* is often referred to as the "Wonder Tree" or the "King of the Desert", reflecting its versatile contributions to both ecological and socio-economic systems. The various parts of *P. cineraria* – leaves, pods, seeds, and bark – are utilized in diverse applications, including as food products such as flour, beverages, vegetables, and gum. The leaves and pods are also employed as feed for ruminants and other livestock. In traditional medicine, *P. cineraria* plays a significant role in treating a range of ailments, including leprosy, dysentery, asthma, leukoderma, dyspepsia, and earache (Afifi & Al-rub, 2018). As a leguminous tree, *P. cineraria* plays a crucial role in enhancing soil fertility by fixing atmospheric nitrogen. Its litter fall production and decomposition rates are among the highest compared to other arid-zone trees. This contributes to an accumulation of soil organic matter beneath its canopy, which in turn increases soluble calcium and available phosphorus levels while lowering soil pH. *P. cineraria* seeds contain 16.5–18.25% protein, which is lower than the 25.47% found in *A. nilotica* and the 38.89% in *A. senegal*. Nevertheless, *P. cineraria* seeds represent a promising and cost-effective protein source for industrial applications, particularly in developing Afro-Asian countries. They offer a viable alternative for addressing protein-energy malnutrition. In addition to protein, the seeds of *P. cineraria* also contain a significant amount of ash (5.34%) and fiber (20.93%) (Balogun & Fetuga, 1986).

The desert legume *P. cineraria* is utilized in traditional medicine for its anthelmintic, antibacterial, antifungal, antiviral, and anticancer properties. Its edible pods are notably rich in essential nutrients, including vitamin C, calcium, and iron. These pods are recognized for their effectiveness in preventing protein-calorie malnutrition and addressing deficiencies in iron and calcium (Asati et al., 2022). *P. cineraria* is found in the dryland forests of southern and western Asia, specifically within tropical thorn forests. It ranks as a dominant species according to the Dominance Candidate Index (DCI) for tree communities in Rajasthan. This evergreen xerophytic tree plays a significant role in the culture and imagination of the region. Adapted to desert environments, *P. cineraria* can withstand temperatures up to 50°C during summer and light frosts in winter. It exhibits high tolerance to water stress, soil salinity and alkalinity, silting, herbivory, and repeated lopping. Moreover, it is capable of absorbing water through its leaves, further enhancing its resilience (Baibout et al., 2022). As a member of the Leguminosae family, trees in the *Prosopis* genus are a crucial source of protein in arid and semi-arid regions. Consequently, *P. cineraria* present a promising and cost-effective protein source for industrial applications, particularly in developing countries. It holds potential as an alternative protein source to address protein-energy malnutrition challenges (Al Ghais et al., 2020). *P. cineraria*, an underutilized edible legume from Rajasthan, India (Figure 3.1), holds potential as a source of bioactives and bioenergy. It is a key ingredient in the traditional Rajasthani dish panchkuta and exemplifies how local communities leverage available resources to fulfill nutritional needs while employing conservation and sustainability practices. The tree is revered in Rajasthan, particularly by the Bishnoi community, who have historically made significant sacrifices to protect it. Ethnomedicinally, *P. cineraria* has been used to treat ailments such as cough, dysentery, leucoderma, rheumatism, microbial infections, worms, and scorpion stings (Singh et al., 2023b). During the hot season from April to June, the tree produces cylindrical green pods containing seeds, which are rich in antioxidants, vitamin C, calcium, and iron. Local communities preserve these pods by boiling, drying, or pickling for use throughout the year. The seeds are also considered a promising option for addressing protein-calorie malnutrition and could be developed into an economic food source. Furthermore, *P. cineraria* pod flour has a low glycemic index, indicating its potential as a healthy alternative to refined wheat flour in products like biscuits (Joshi et al., 2024).

3.1.6 *Cyamopsis tetragonoloba* (L.) (Taub)

C. tetragonoloba, commonly known as guar, is a hardy desert legume with significant potential for enhancing human food security and sustainability (Figure 3.42). Originating from arid regions of India and Pakistan, guar is well-adapted to harsh environmental conditions, including high temperatures and low water availability. This drought-resistant plant is renowned for its high protein content and unique polysaccharide, guar gum, which has diverse industrial and food applications. Guar can contribute to food security by providing a nutritious, sustainable alternative to more water-intensive crops. Its cultivation supports sustainable agricultural practices by improving soil health and requiring minimal irrigation, making it an ideal candidate for expanding food resources in arid and semi-arid regions (Soltani et al., 2021). Guar gum is a natural polymer with significant potential for pharmaceutical applications, owing to its distinctive composition and non-toxic nature. Its versatility allows it to be tailored for various requirements in biological and medical engineering fields. In the creation of advanced drug delivery systems, Guar gum is frequently employed as a rate-controlling excipient, facilitating precise and controlled release of therapeutic agents. Guar Gum is an annual crop cultivated in Asia (India and Pakistan), North Africa, and South America. It is derived from the ground endosperm of *C. tetragonolobus* (Leguminosae family). The gum's structure features a linear backbone of 1,4-linked D-mannose units (M) that is solubilized by the presence of randomly attached 1,6-linked galactose units (G) as side chains (Gong et al., 2012; Meftahizadeh et al., 2019).

Guar (*C. tetragonoloba*) is a versatile summer legume crop utilized for its seed gum, derived from its galactomannan content, and for its high-protein by-products, including the germ and hull, which are used in animal feed. Guar gum (GG), extracted from the seed's endosperm,

FIGURE 3.42 *Cyamopsis tetragonoloba.*

is a polymer composed of mannose and galactose units, known as galactomannans (Chiofalo et al., 2018). GG is widely employed as an emulsifier, thickener, and stabilizer across various industries, including food, paper, textiles, cosmetics, and oil. Following gum extraction, the by-products from the GG industry include the seed coat and germ, which make up approximately 44% and 21% of the guar seed, respectively (Salehpour et al., 2012). *C. tetragonoloba* is a legume primarily grown for industrial applications due to the galactomannans present in its endosperm. Additionally, its by-product serves as a valuable ingredient in animal feed. Guar is a low-emission, summer crop with excellent drought resistance and the ability to fix atmospheric nitrogen, making it a beneficial component in crop rotation systems. Guar gum, a hydrocolloid extracted from the seed, hydrates rapidly in cold water, forming a thick, high-viscosity solution. After the gum is extracted, the remaining components of the seed, specifically the seed coat and germ, constitute approximately 60% of the whole seed and are referred to as guar meal. This by-product also has significant economic value. The guar bean contains antinutritional factors, necessitating thermal treatment when fed as whole grain. Despite this, guar protein exhibits a well-balanced amino acid profile. The protein content in the embryo and spermoderm ranges from 28.9% to 46.0%. In guar fodder, the embryos and husks constitute approximately 25% and 75% of the raw material, respectively. Chemically, guar gum is a non-ionic polysaccharide characterized by a mannose backbone with attached galactose side chains (Dzyubenko et al., 2017).

The endosperm polysaccharide of the guar seed is a key water-soluble gum, with an estimated global market of 150,000 tons annually, owing to its distinctive rheological properties. GG finds extensive use across various industrial sectors, including the food industry (Liyanage et al., 2015). Guar is a self-pollinating plant with minimal cross-pollination. Its origins remain uncertain, as it has not been identified in the wild. The prevailing theory suggests that guar may have descended from *C. senegalensis*, which has its center of origin in Africa or the Arabian Peninsula. It is believed that the plant was introduced to India by Arabs, either as flotsam or as feed during horse trade, where it was subsequently domesticated (Mathur, 2012). Guar exhibits exceptional heat and drought tolerance, comparable to other crops grown in the Mediterranean region. It thrives in sandy soils but can also grow in well-ploughed and well-drained clay soils, although it is highly sensitive to waterlogging. Additionally, guar is adaptable to soils with low fertility and high salinity (Gresta et al., 2018). Guar exhibits high drought resilience and can adapt to soil degradation with minimal surface water requirements. It thrives under intense sunlight and low relative humidity during the growing season. Consequently, guar has become a sustainable income source in arid and semi-arid regions. It is one of the most cost-effective sources of galactomannans. In the guar gum production process, the endosperm is separated from the hull and embryo through a series of grinding and sifting stages (Soltani et al., 2021). Further physical treatments are employed to break the seed and separate its components. The guar seed endosperm, which contains galactomannan, is distinct from the germ, which is primarily composed of protein. The endosperm, or guar split, is commercially available and can be processed into powder to produce GG. Various purification methods are used for GG, including the application of proteolytic enzymes linked to its botanical significance in desert environments (Khodayari et al., 2021; Sanaei et al., 2022).

Guar is economically significant and often referred to as the "heart of the farmer's fields", with India accounting for 80% of global guar gum production. Guar has various applications, including use as a laxative, digestive aid, appetizer, or cooling agent. Guar gum holds potential benefits for individuals with hypercholesterolemia and insulin-dependent diabetes by improving glycemic control and reducing serum LDL-cholesterol levels. Furthermore, due to its content of several therapeutically active compounds, such as quercetin, daidzein, and kaempferol, guar is utilized as a complementary medicinal plant in desert food traditions (Joshi et al., 2023). The guar seed comprises 43–47% germ, 30–33% hull, and 27–30% endosperm by weight. Global production of guar seeds ranges from 1.0 to 1.6 million tons annually, with India being the largest producer, contributing 80% of the world supply, followed by Pakistan with 15%. Within India, Rajasthan is the primary producer, accounting for 70% of the country's output, while Haryana contributes 12%, Gujarat 11%,

and Punjab 3%. Guar meal, a by-product of the guar gum extraction process, consists of the germ and hull of the guar seeds and contains 30–60% crude protein (Nidhina & Muthukumar, 2015). It is produced after separating the endosperm from the germ and hull of *C. tetragonolobus*. Research on enhancing the applicability of guar meal or its protein for human food is limited. Some studies have addressed the extraction, characterization, functional properties, and protein isolation of guar meal. Currently, guar meal has minimal use in human food applications due to the presence of anti-nutritional factors such as trypsin inhibitors, saponins, residual gum, lignin, polyphenols, and certain organic acids and aldehydes, which contribute to its undesirable smell and bitter taste (Kotnala et al., 2024).

3.1.7 *Crotalaria burhia* Buch.-Ham. ex Benth.

C. burhia, a lesser-known legume species, has emerged as a valuable crop for arid and semi-arid regions due to its adaptability to desert ecosystems (Figure 3.43). This legume, belonging to the genus *Crotalaria* within the Fabaceae family, exhibits remarkable resilience and growth potential in extreme environmental conditions where traditional crops struggle. The ecological significance of *C. burhia* is underscored by its ability to thrive in low-water environments and its contribution to soil health through biological nitrogen fixation. In desert ecosystems, where soil fertility is often compromised and water availability is limited, *C. burhia* presents a sustainable solution for enhancing soil quality and providing a reliable food source. Its deep root system enables it to access moisture from deeper soil layers, mitigating the impacts of drought and soil degradation. Furthermore, the plant's capacity to fix atmospheric nitrogen enriches the soil with essential nutrients, reducing the need for synthetic fertilizers and promoting a more sustainable agricultural practice. This legume adaptability is also reflected in its tolerance to high temperatures and poor

FIGURE 3.43 *Crotalaria burhia.*

soil conditions, making it an ideal candidate for cultivation in regions characterized by extreme climatic conditions. The seeds of *C. burhia* are not only a potential food source but also serve as a fodder crop, offering nutritional benefits for livestock. This dual-purpose functionality underscores its importance in improving food security and agricultural resilience in desert environments. Research into the cultivation practices, yield potential, and nutritional profile of *C. burhia* is essential for maximizing its benefits and integrating it into sustainable agricultural systems. As global challenges related to climate change and resource scarcity intensify, the exploration and development of hardy crops like *C. burhia* will be crucial for advancing agricultural productivity and food security in arid regions. Its role in enhancing soil health, providing nutritional value, and supporting ecosystem sustainability highlights the potential of this legume as a key component in the future of desert agriculture (Arora & Chandel, 1972).

C. burhia, a herbaceous member of the Leguminaceae family, is predominantly found in arid regions of India, Pakistan, China, and Afghanistan. This plant is traditionally employed in the treatment of a range of conditions including gout, eczema, hydrophobia, and inflammation. The porridge made from its root is utilized for addressing typhoid, wounds, cuts, rheumatism, flatulence, earaches, nasal bleeding, and renal issues. Additionally, the powdered form of *C. burhia* is used to manage digestive disorders. The plant is noted for its significant pharmacological properties, exhibiting both carcinogenic and anticarcinogenic effects. It contains a variety of phytoconstituents, such as tannins, amino acids, alkaloids, steroids, triterpenoids, mucilage, flavonoids, gum, polyphenols, anthraquinones, carbohydrates, glycosides, and saponins. A notable compound derived from *C. burhia* is croburhine, a novel pyrrolizidine alkaloid with distinct biological activities (Wal et al., 2024). *C. burhia*, a member of the Fabaceae family, is one of approximately 700 species within this family, which is distributed across tropical and subtropical regions worldwide. In the arid regions of West Pakistan, India, and Afghanistan, *C. burhia*, also known as Khip, is found as a shrub with fibrous characteristics. Historically, the ancient Indian Ayurvedic system has recognized this plant for its considerable medicinal value (Anwar et al., 2022). The leaves, roots, and branches of *C. burhia* exhibit anticancer and soothing properties, while the fresh plant juice is utilized in traditional medicine to treat a variety of conditions including eczema, gout, hydrophobia, pain, and edema. An extract of the roots combined with sugar is used specifically for alleviating chronic kidney pain and treating typhoid fever. The plant's diverse medicinal properties extend to the preparation of cooling medications from its leaves, branches, and roots (Talaviya et al., 2018). *C. burhia* is also employed as an effective soil binder, a forage source for goats, and for constructing shelters and ropes in desert environments (Soni, 2014). *C. burhia*, thriving in arid environments such as sand dunes, serves as a stabilizer for these unstable soils. The plant branches are notably robust and are utilized in the production of ropes and cordage due to their strength and resistance to decay (Panwar et al., 2014).

Preliminary investigations have revealed that *C. burhia* contains a range of bioactive compounds, including alkaloids, flavonoids, triterpenoids, quercetin, saponins, steroids, and phenols. Existing literature indicates that the plant extract exhibits significant biological activities, such as antibacterial, antimicrobial, anti-inflammatory, and antinociceptive effects. Furthermore, the roots of *C. burhia* demonstrate potent antioxidant and antitumor properties (Kataria et al., 2011). This plant is well-regarded for its efficacy in treating prevalent infections in the Thal Desert region of Punjab (Niaz et al., 2013). Preliminary phytochemical screening of methanol and dichloromethane (DCM) extracts from the aerial and root parts of *C. burhia* has led to a comprehensive analysis of their bioactive content. The results indicate that the methanolic root extract exhibits the highest total phenolic content, notably containing elevated levels of epicatechin and p-coumaric acid (Anwar et al., 2024). High-performance thin-layer chromatography (HPTLC) profiling of *C. burhia* has identified the presence of the anticancer agent monocrotaline. Phytochemical analyses have also detected various alkaloids, including crotalarin, monocrotaline, croburhine, and crosemperine. Furthermore, the isolation of certain flavonoids, such as quercetin, and steroids, including β-sitosterol, has been confirmed (Aslam et al., 2024; Noor et al., 2022).

3.1.8 *Parkinsonia aculeata* L.

P. aculeata, commonly known as the Jerusalem thorn, is increasingly recognized for its potential as a valuable legume in desert rangeland systems (Figure 3.44). This drought-tolerant shrub not only thrives in arid environments but also offers significant benefits as a source of food protein and sustainability. Its ability to fix nitrogen enhances soil fertility, while its protein-rich pods provide a vital nutritional resource for both livestock and human consumption. As desertification and food security become pressing global concerns, *P. aculeata* emerges as a promising candidate for improving rangeland productivity and resilience, making it a key player in the sustainable management of arid and semi-arid landscapes. *P. aculeata*, a member of the Fabaceae family, is a prominent native species in the Sonoran semi-desert. The genus Parkinsonia includes four species in northwestern Mexico, where arid conditions prevail. Notable variability in soil conditions is observed in northwest Mexico, home to the Sonoran semi-desert, which experiences high levels of drought, salinity, and extreme temperatures (Awwad et al., 2023). The abundant populations of palo verde in these regions play a crucial role in maintaining ecosystem functionality. This species is well-adapted to a range of challenging edaphoclimatic conditions, thriving in soils affected by both drought and salinity (Peñuelas-Rubio et al., 2024). The palo verde, originally native to semi-desert regions, has since spread globally, showing adaptability to both favorable and adverse environmental conditions. Despite initial research being limited and somewhat scattered, recent investigations aimed to update the species' international distribution and primary applications. The results indicate that palo verde is now found on every continent, with significant findings in the Americas, Africa, and Australia. It thrives at elevations ranging from 8.6 to 1310 meters above sea level and demonstrates resilience

FIGURE 3.44 *Parkinsonia aculeate.*

to heat, drought, salinity, and waterlogging. However, it is sensitive to cold climates, with only one recorded instance in North Asia (Argentel-Martínez et al., 2023).

This species is likely due to its native habitat and has developed biochemical mechanisms that enable it to adapt to various stressful conditions across different ecosystems globally (Mukherjee et al., 2021). Consequently, it holds potential as a valuable resource for combating desertification and supporting the recovery of fragile and degraded ecosystems (Calvo-Alvarado et al., 2022). A survey of the genus *Parkinsonia* has identified a diverse array of compounds, including flavones, flavanones, flavone C-glycosides, alkaloids, sterols, tannins, terpenoids, glycerols, carotenoids, saponins, and carbohydrates, as well as free amino and fatty acids (Hassan et al., 2019). *P. aculeata* is associated with various health benefits, including antioxidant, hypoglycemic (noted in the aqueous fractions of the aerial parts and bark), hepatoprotective (from leaf extracts), anti-spermatogenic (attributed to the ethanolic extract of the stem bark), antimalarial (found in flowers and leaves), amoebicidal, smooth muscle stimulant, analgesic, anti-inflammatory, and antipyretic (reported in total alcoholic and aqueous leaf extracts) activities. Orally, the hot aqueous extract of its leaves has been used as an abortifacient in pregnant women (Abdelaziz et al., 2020). The antimicrobial activity observed in the leaves, stem, and flowers is likely due to the presence of alkaloids, while the antimicrobial properties of the dried aerial parts and stem bark are attributed to compounds such as β-amyrin, palmitic acid, β-amyrone, β-sitosterol, β-sitoeryl-β-D-glucoside, glycerol β-butanoate, and daucosterol. Additionally, the antimicrobial effects of dried seeds are linked to the presence of L-dopa and tryptophan amino acids (Gupta et al., 2011; Sharma et al., 2014).

P. aculeata has a long history of use in ethnomedicine by local populations and traditional healers for managing hyperglycemia. Araújo et al. (2016) elucidates its hypoglycemic effects, showing that treatment with the HEPa/EtOAc fraction effectively ameliorates insulin resistance induced by a high-fat diet in obese mice. Specifically, HEPa/EtOAc treatment significantly enhances insulin sensitivity and normalizes fasting serum levels of glucose, insulin, and leptin, while having minimal impact on body weight. The leaves of *P. aculeata* have been reported to contain C-glycosylflavones, including orientin, iso-orientin, vitexin, and iso-vitexin. Furthermore, other constituents identified in the leaves include C-glycosides such as epi-orientin, the C-glycoside of luteolin, and Parkinsonin-A (Sharma et al., 2018). *P. aculeata* is recognized for its tolerance to water stress and often forms dense, thorny thickets that are difficult to penetrate, particularly along drainage lines, depressions, and seasonal wetlands. The species is capable of growing even when its root systems are submerged, and it can endure prolonged periods over nine months with the lower portion of its trunk underwater (Calvo-Alvarado et al., 2022). *P. aculeata*, a tree native to the semi-arid Xingó region in Northeastern Brazil, is traditionally used by local communities for managing diabetes and dyslipidemias (Leite et al., 2007). Based on local practices, the plant's aerial parts are typically prepared as an infusion, using approximately 15 grams of the plant material, and consumed throughout the day (Franco et al., 2022). Crushed young twigs of *P. aculeata* are reported to be used in the treatment of tumors, while an infusion of the dried flowers is taken orally for its antipyretic and diaphoretic properties. Moreover, a decoction made from the leaves, fruit, and stems of *P. aculeata* is used to treat fever and malaria (Elgaml et al., 2020). In a study by Awwad et al. (2023), both chromatographic (LC-MS and GC-MS) and biological evaluations conducted on *P. aculeata* revealed that trans-ocimene was the predominant monoterpene in the aroma profiles of all studied plant organs, while the hydro-distilled oils contained higher percentages of non-terpenoid volatile compounds. LC-MS analysis of the water extract from the aerial parts identified 16 compounds, with 4-methylumbelliferone, succinic acid, vitexin, and hyperoside being the most prominent. The ethanol extract of the aerial parts contained eleven identified compounds, with iso-orientin and chrysoeriol-7-glucoside as the major components. Biologically, the water extract demonstrated significant antiproliferative activity against four tested cell lines, with IC50 values ranging from 17.5 to 77 μg/mL.

3.1.9 *Prosopis juliflora* (Swartz) DC

P. juliflora, commonly known as mesquite, is a versatile leguminous tree native to arid and semi-arid regions (Figure 3.45). Its ability to thrive in harsh desert environments makes it a valuable resource for enhancing food security and nutrition in areas prone to drought and soil degradation. The tree's pods are rich in essential nutrients, including protein, fiber, and minerals, making them an excellent food source for human consumption. The nutritional profile of *P. juliflora* contributes to its potential as a sustainable food option, capable of supporting dietary needs in regions where conventional crops may struggle. Additionally, the tree's adaptability to extreme conditions and low water requirements makes it a resilient choice for improving food security in vulnerable areas. *P. juliflora* also offers environmental advantages, such as soil improvement through nitrogen fixation and erosion control, further supporting its role in sustainable agricultural practices. *P. juliflora* role in food systems of native communities in desert zones can address both immediate nutritional needs and long-term food security challenges promoting environmental health and resilience (Patil et al., 2016). *P. juliflora*, a member of the Leguminosae (Mimosaceae) family, is widely recognized for its efficacy in treating diabetes mellitus. According to the World Health Organization (WHO), approximately 80% of the global population relies on herbal remedies for disease management due to their accessibility, cost-effectiveness, and lower side effects compared to conventional medicine. This plant exhibits extensive ecological adaptability, thriving in a variety of soil types and environmental conditions. It is particularly suited to areas where water scarcity and soil fertility are major constraints on plant growth, and it can endure and prosper in some of the nutrient-poor soils that are inhospitable to other tree species (Ukande et al., 2019).

P. juliflora, a xerophyte by nature, has traditionally thrived in desert environments within its native range. While it remained within its indigenous habitat, *P. juliflora* served as a valuable resource, particularly for economically disadvantaged communities, who utilized every part of the tree for various benefits (Patnaik et al., 2017). *P. juliflora* is among the introduced species utilized for the restoration of marginal and degraded lands in various countries. While the introduction of *P. juliflora* has yielded some positive effects in arid and semi-arid regions worldwide, it is important to acknowledge both the benefits and potential challenges associated with its deployment (Edrisi

FIGURE 3.45 *Prosopis juliflora.*

et al., 2020). *P. juliflora* is notably invasive in non-native environments and has been classified as one of the world's 100 most invasive species, with a global distribution. This invasiveness is largely attributed to the allelochemicals it releases from its roots, leaves, and fruits, which inhibit the seed germination of surrounding plant species. *P. juliflora* can lead to ecosystem-level changes, forming dense, monospecific stands that alter soil chemistry and biophysical properties (de Souza Nascimento et al., 2014). The allelopathic effects of *P. juliflora* are due to metabolites produced through two primary biosynthetic pathways: shikimic acid derivatives and piperidine alkaloids. While several *Prosopis* species significantly impact biodiversity, ecosystem services, and local economies in their native regions, others offer various benefits to local communities. *P. juliflora* proves to be a versatile raw material with applications across food, cosmetics, pharmaceuticals, agriculture, and renewable energy sectors, advancing multiple fields of science and technology (de Brito Damasceno et al., 2020).

P. juliflora is extensively used as livestock feed, and its by-product, the grain, holds significant potential as a human food source. This species is notable for its ability to withstand periodic droughts common in semi-arid regions (González-Montemayor et al., 2019). While it serves as a valuable livestock input, its high nutritional quality makes it a promising ingredient for human consumption. Research has focused on utilizing the entire mesquite pod in human food products, such as mesquite pod flour for baking cookies and bread. The grain constitutes 10–15% of the pod weight, highlighting the importance of exploring its potential for human dietary applications (de Melo Cavalcante et al., 2022). *P. juliflora* is a xerophytic, nitrogen-fixing plant. Its fruit consists of pods containing seeds, both of which are rich in nutritional value and bioactive compounds. Various derivatives can be produced from the pods and seeds, including flour, starch, syrup, protein concentrate, and gums. Extracts from the bark, flowers, pods, and leaves of *P. juliflora* have been found useful in treating asthma. The leaves, in particular, can help mitigate hepatic necrosis, exhibit anticancer properties, and are employed in headache relief. Additionally, an ethanolic extract of *P. juliflora* leaves, when combined with chitosan, has been studied and characterized for its antimicrobial properties. This extract-chitosan combination was effectively used as a coating for strawberries, demonstrating efficiency against various spoilage agents. For extending the shelf life of strawberries stored at low temperatures (4°C), a 1% chitosan-coated *P. juliflora* leaf ethanolic extract is recommended (de Lemos et al., 2023). The wood of *P. juliflora* is utilized as a source of charcoal and activated carbon and is also employed in the production of paperboard, paper, and hardboard. Moreover, the pods are used as animal feed, while the flowers provide nectar for honey production by bees (Yadav & Rana, 2020). Drought-tolerant genes have been identified in *P. juliflora* through the use of expressed sequence tags. These genes are subsequently employed to enhance drought resistance in various transgenic crops and plants (Ukande et al., 2019).

The extracts from the leaves and fruit of *P. juliflora* were tested for their ability to inhibit various bacteria, yeast, and fungi that produce mycotoxins. The water-soluble ethanolic leaf extract demonstrated the strongest antibacterial properties. It completely inhibited the growth of several pathogens, including *Botrytis cinerea*, *Alternaria alternata*, *Bacillus subtilis*, *Staphylococcus aureus*, and *Candida albicans*, with minimum inhibitory concentrations (MICs) ranging from 0.125 to 1 mg/ml. The extract also significantly inhibited the mycelial growth of seven other fungal strains, with the highest inhibition (66.2%) observed against *Geotrichum candidum*. Under a scanning electron microscope, the extract caused noticeable damage to fungal structures, such as flakes, pores, and vacuolation. In small-scale tests, water-soluble ethanolic leaf extract effectively protected cherry tomatoes from infections caused by *B. cinerea* and *Alternaria alternata* (Saleh & Abu-Dieyeh, 2021). For thousands of years, the pods of *P. juliflora* have been used as food for humans and livestock in arid and semi-arid regions, owing to their high sugar and protein content. When manually ground, the pods produce flour that is utilized in various culinary applications, such as beverages and jellies. Alkaloids and alkaloid-rich extracts from this plant have demonstrated a broad range of in vitro antimicrobial activities against various microorganisms, including bacteria, fungi, and protozoa (Batista et al., 2018). *P. juliflora* has various applications, including the restoration of

contaminated or degraded land, phytoremediation, CO_2 sequestration, and carbonation technology. It is also used in the production of bioethanol and offers opportunities for value addition and value chain products. Furthermore, this plant has medicinal uses and provides a range of ecosystem services (Prasad & Tewari, 2016).

3.1.10 *Tephrosia purpurea* (L.) Pers.

T. purpurea, commonly known as the purple tephrosia or wild indigo, emerges as a promising desert legume species with significant potential for human food sustainability (Figure 3.46). This hardy perennial legume is native to arid and semi-arid regions, exhibiting remarkable adaptability to harsh environmental conditions such as low soil fertility, extreme temperatures, and minimal water availability. Its resilience makes it a valuable candidate for cultivation in desert ecosystems, where conventional crops often struggle. Rich in protein, essential amino acids, and beneficial phytochemicals, *T. purpurea* offers a nutritional advantage, providing a vital source of sustenance in regions prone to food insecurity. Beyond its nutritional benefits, this species contributes to soil fertility through nitrogen fixation, enhancing the sustainability of agricultural practices in arid environments. Its potential for incorporation into local food systems, coupled with its ability to improve soil health, underscores its role in advancing food security and ecological balance. This introduction explores the botanical characteristics, ecological advantages, and potential applications of *T. purpurea*, emphasizing its importance in developing sustainable food sources for desert regions (Kumari et al., 2018). *T. purpurea* belonging to the Fabaceae family is commonly known

FIGURE 3.46 *Tephrosia purpurea.*

as Sarapunkha. This extensively branched, sub-erect, herbaceous perennial is a key component in Ayurvedic medicine, where it is referred to as "wranvishapaka", signifying its wound-healing properties. It plays a crucial role in Ayurvedic formulations such as Tephroli and Yakrifit, which are used to address liver disorders. Furthermore, the plant has applications in treating asthma, impotence, diarrhea, rheumatism, gonorrhea, and ulcers, as well as urinary and cardiovascular conditions. The dried herb is recognized for its tonic laxative, diuretic, and deobstruent effects (Aneshwari et al., 2022).

Ayurvedic medicine recognizes *T. purpurea* for its diverse therapeutic properties and effects on the human body. In Ayurveda, plants are characterized by specific qualities or 'gunas' that determine their therapeutic actions. *T. purpurea* thrives in various environments, including open forests, grasslands, wastelands, and rocky slopes, and is commonly found along roadsides, in disturbed areas, and in arid regions. It can grow in different soil types such as sandy, loamy, and clay soils, but it prefers well-drained soils with a slightly acidic to neutral pH (Rani & Raju, 2021). Traditionally, the seeds of *T. purpurea* have been used as a food source in certain regions, following thorough processing to remove toxic compounds through soaking, boiling, or roasting. The young leaves of the plant are also consumed as leafy vegetables in some cultures, though proper preparation is essential to eliminate any potential toxins. Furthermore, the flowers of *T. purpurea* are used in traditional cuisines, often featured in salads or cooked dishes (Kumar et al., 2024a). *T. purpurea* has a well-documented history of ethnopharmacological use, as highlighted in ancient literature. It plays a significant role in traditional herbal preparations such as Tephroli and Yakrifti, which are utilized for treating liver disorders. Known for its efficacy in addressing inflammation and enlargement of the liver and spleen, it is also referred to as plihari or plihasathru, with "plihari" indicating its use for spleen-related issues. The roots and seeds of the plant exhibit piscicidal and insecticidal properties and are used as vermifuges (Akanksha et al., 2014). Phytochemical analyses confirm the presence of various bioactive compounds, including rotenoids, flavanols, glycosides, isoflavones, sterols, and chalcones. Seed oil is effective in treating scabies, eczema, cirrhosis, and other skin conditions. Moreover, a decoction of the fruit is used to eliminate intestinal worms, while fruit extract has been found beneficial for inflammatory issues and body pain. Further investigation of *T. purpurea* roots using a petrol-soluble fraction of chloroform extract and silica gel chromatography identified four compounds: maackiain, purpurenone, dehydrolsodericin, and purpurin, along with a mixture of pseudosemiglabrin and semiglabrin determined by N.M.R. data (Rao et al., 2020).

T. purpurea subsp. apollinea is a plant that contains several compounds with potential health benefits. These include stigmasta-14,5,24(28)-dien-3-ol, 9,12,15-octadecatrienoic acid methyl ester, phytol, chlorogenic acid, and quercetin. These compounds show promise in fighting cancer and have antioxidant properties. The exploration of their effects on various cancer types such as breast cancer (MCF7), osteosarcoma (MG63), breast ductal carcinoma (T47D), cervical cancer (HeLa), and prostate cancer (PC3). However, the plant's effect on leukemia is weak, and it doesn't significantly harm healthy cells (Youssef et al., 2023). In Unani medicine, *T. purpurea* is used to treat a range of conditions including kidney issues, cough, asthma, pain, inflammation, vomiting, boils, acne, indigestion, hemorrhoids, skin disorders, and wounds. Furthermore, it has been noted for its laxative, diuretic, insecticidal, fish-poisoning, and anti-parasitic properties (Ansari & Jahan, 2019). Traditionally, the plant is also employed to address jaundice, liver enlargement, poisoning, abdominal swelling, and spleen enlargement (Abdel-Kader et al., 2024). The powdered root of *T. purpurea* is used for brushing teeth, as it is believed to quickly alleviate dental pain and stop bleeding. African shepherds use crushed parts of the plant to prepare an antidote for animals that have been bitten by snakes. *T. purpurea* has shown that its alcohol extract exhibits significant hydroxyl radical scavenging activity in laboratory tests. Moreover, the extract has been found to significantly improve the viability of isolated rat kidney cortical cells that were damaged by gentamicin, according to a Trypan blue exclusion assay (Nigam, 2021). Its ability to cross-link helps promote the maturation and repair of collagen. However, its antioxidants protect the body from free radical damage by neutralizing superoxide radicals (Khan et al., 2024).

3.2 PRICKLY PEAR: LOW-COST FORAGE CROP FOR SUPPLEMENTING FOOD SECURITY

Cacti deliver substantial livelihood benefits and vital ecosystem services. They offer provisioning services such as food for humans, livestock feed, and medicinal uses. Cacti also provide supporting services by supplying wildlife with food, pollen, habitat, and shelter. Their regulating services include controlling soil erosion, offering mulching material, and sequestering carbon. Furthermore, cacti contribute cultural services, such as forming live fences. For impoverished farmers in degraded areas, cacti are a crucial asset, enhancing both their livelihoods and environmental conditions (Meaza et al., 2024). The cactus *Opuntia*, commonly known as prickly pear or cactus pear, is a tropical and subtropical plant in the Cactaceae family, a dicotyledonous angiosperm group that includes around 1,500 cactus species. *Opuntia* is the most widely cultivated and recognized species within its genus, which encompasses approximately 300 species globally. Among these, about 15 species are extensively cultivated in arid and semi-arid regions for their edible fruits, young cladodes used as vegetables, and cladodes utilized as forage (Pastorelli et al., 2022). Prickly pear (*Opuntia spp.*), a type of cactus native to the Americas, offers a promising solution for enhancing food security in arid and semi-arid regions. Characterized by its low water requirements and high resilience to harsh environmental conditions, prickly pear serves as an invaluable forage crop that can thrive in desert landscapes where conventional crops may struggle (Iqbal et al., 2020). This hardy plant not only provides a sustainable source of nutrition for livestock but also produces edible fruits and pads that are rich in essential nutrients for human consumption (Hamid et al., 2020). The cultivation of prickly pear is particularly advantageous in areas facing water scarcity and soil degradation, as it requires minimal irrigation and can improve soil health through its deep root system (Arba, 2020). Furthermore, the plant's ability to produce high yields with limited resources makes it a cost-effective alternative to traditional forage crops, thereby contributing to local food security and economic stability (Kumar & Singh, 2021). The incorporation of prickly pear into agricultural systems, communities can diversify their food sources, enhance livestock nutrition, and strengthen resilience against climate variability, thus playing a crucial role in sustainable development and food sovereignty in desert environments (Ahmed & Elsamani, 2024).

3.2.1 *Opuntia dillenii* (Ker Gawl.)

The family Cactaceae contains the genus *Opuntia*, native to the USA and belonging to the subfamily Opuntioideae, including 2,300 species approximately (Majure, 2010; Powell & Weedin, 2004). *Opuntia* plant species have the capability to grow in all tropical, arid, and temperate climatic conditions (Butera et al., 2002; Lallouche et al., 2015). *Opuntia* are highly adaptable in arid and semi-arid conditions and extreme environments such as high temperature, UV radiation, and drought (Reyes-Agüero & Aguirre-Rivera, 2011; Stintzing & Carle, 2005). *Opuntia* present worldwide in the arid regions of Brazil, Mexico, western Asia, and northern and southern regions of Africa and have been used extensively as medicinal plants, ornamental plants, forage crops, and foodstuffs (Majure & Ervin, 2008). *Opuntia* are wildly grown xerophytic plants with C.A.M. metabolism found frequently in regions with dry sunny conditions, that withstand high temperature, water shortage, and less fertile soil conditions around other deep-rooted plants (Liu et al., 2009). *Opuntia* plant species contains vital nutrients (betalains, organic acids, minerals, vitamins, polysaccharides, phenolic compounds, lipids, and amino acids) significant for health food and medicine production (Zhao et al., 2011). With water-limiting reservoirs and spreading of desertification worldwide, *Opuntia* spp. vegetative and fruit parts are significantly effective in food production. *Opuntia* plants are spread in 1 million hectares and used in more than 30 countries for their vegetables and fruit (Stintzing & Carle, 2005). *Opuntia dillenii* features a diverse phytochemical profile, including flavonoids, alkaloids, and polysaccharides, which contribute to its antioxidant, anti-inflammatory, and glycemic-regulating properties. Ethnopharmacological

research demonstrates its traditional medicinal uses, particularly in managing diabetes, hypertension, and gastrointestinal issues, highlighting its therapeutic efficacy. Ethnobotanically, *O. dillenii* is integral to desert zone communities for its nutritional value, versatility as a food source, and role in sustainable agricultural practices, reflecting its deep-rooted cultural and practical significance (Lu et al., 2023).

O. dillenii knowledge habitually as succulent shrubby plant in tropical and subtropical semi desert areas commonly known as prickly pear (Figure 3.47). Commonly called tuna and pear bush in English, Chittar thohar in Punjabi, and Nagphana in Hindi (Ejaz et al., 2014). This plant is native to the islands of the USA and the West Indies; however, it is distributed widely due to cultivation in the African continent, Canary Islands, Australia, India, and Pakistan (Pooja & Vidyasagar, 2016). This plant contains important nutrients such as betalains, flavonoids, phenolics, polysaccharides, minerals, and vitamins. *O. dillenii* has been widely used for brewing, as a vegetable source, and as additives in food and fodder (Medina et al., 2007; Zhao et al., 2012). It is traditionally used in several areas of Pakistan for the treatment of inflammation, with ten drops dosage of milky juice coupled with mashed leaves (Mahmood et al., 2011), as well for treatment of gastric ulcer, diabetes (Qiu et al., 2007), ophthalmia, asthma, intestinal convulsions, hepatitis, and whooping cough (Loro et al., 1999). This plant is used locally as herbal medicine in several countries to stimulate detumescent drainage and blood circulation, and it also has anti-inflammatory and antioxidative properties (Zhao et al., 2012). The stem vegetative segments (cladode), together with fruits of *O. dillenii*, is revealed to have supportive health activities that are safe, edible, and non-toxic for humans as fresh vegetables (Gao et al., 2015; Kalegowda et al., 2017). Stem cladode segments and fruit are being used against gastric ulcers, inflammation, and diabetes (Liu et al., 2009).

FIGURE 3.47 *Opuntia dillenii.*

Opuntia has exhibits potential for antihyperlipidemic, antiviral, anti-inflammatory, anti-diabetic, antioxidant, and antiulcerogenic pharmacological activities. It has been documented for the treatment of Alzheimer's disease, Parkinson's disease, strokes, and protection of nerve cells. Over the past few years, the natural resources' usage as antioxidants and foodstuffs has been spreading globally (Saleem et al., 2005). Its cladodes demonstrate antioxidant, anti-asthmatic, hypoglycemic, antimicrobial, hypotensive, and hypolipidemic, analgesic, and anti-inflammatory effects (Siddiqui et al., 2016). It is also antihyperglycemic; it is used for treatment of gonorrhea and hypotensive activity; and it has preventive ramification against low-density lipoprotein (Bajaj & Gupta, 2012). It was also reported to have anti-spermatogenic activity (Jiang et al., 2006).

It is a shrubby succulent, 20–50 cm, with flattened, elliptical, and oblong cladodes and frequent surface stout spines (Böhm 2008). In microscopic studies, the stem epidermal section consists of irregular shaped cells with straight anticlinal walls. The epidermal cell length is 37.40 μm and the width is 27.85 μm. The stomata of the paracytic type was observed; its length is 37.35 μm and its width is 17.60 μm. Flowers of yellowish-orange color and axillary arranged cladodes position on stem axis. Perianth are rotated with obovate petals and numerous stamens. The fruit is edible and contains many rounded seeds. Pollen are monad, large-sized, pantoporate, and circular in the polar view, while the shape is prolate spheroidal in the equatorial view. Pollen diameter is 121.4 μm (polar axis length), 108.3 μm (equatorial diameter), P/E ratio 1.12 μm, aperture length 20.37 μm, width 18.50 μm, and exine thickness 9.90 μm (Figure 3.48).

The demand for herbal drugs has been increased to ensure their safety, quality, and efficacy over the last two decades (Ahmad et al., 2018a). In literature, phytochemical screening showed the presence of flavonoids, organic compounds, phenolics, fatty acids, steroids, polysaccharides, and amino acids *O. dillenii* (Chang et al., 2008; Chinedu et al., 2017; Moussa-Ayoub et al., 2016; Rayan et al., 2018). The presence of betalian compounds (betacyanin and betaxanthins) were found in *O. dillenii* fruit (Betancourt et al., 2017; Cejudo-Bastante et al., 2015; Embaby et al., 2016; Kalegowda et al., 2015; Moussa-Ayoub et al., 2016). A total of 28 different classes of bioactive chemical compounds were found in *O. dillenii*. The details of important classes of compounds are mentioned in Table 3.3.

Betalain compounds are present in a limited number of plant families of order Caryophyllales (Cejudo-Bastante et al., 2015). The most promising betalain sources are red beet, amaranth, and common prickly pear *O. dillenii* (Ramamoorthy et al., 2016). New sources of betalains have been tested to be used as natural colorants. However, very few investigations of betalains found in *O. dillenii* have been carried out to the best of our knowledge. The chemical characterization has identified several betalain compounds in *O. dillenii*, including betacyanins; 17-decarboxybetanin, 17-decarboxyisobetanin, 6′-O-sinapoyl-O-gomphrenin, 6′-O-sinapoyl-O-isogomphrenin, 2′-O-apiosyl-4-O-phyllocactin, 5″-O-E-sinapoyl-2′-apiosyl-phyllocactin and betaxanthins including tryptophan betaxanthin and tyrosine betaxanthin (Betancourt et al., 2017).

Flavonoid compounds are documented as potential factors present in fruits and vegetables that are very valuable to human health through antioxidant, anticarcinogenic, and anti-inflammatory uses. The seeds of *O. dillenii* contained the highest amounts catechin, epicatechin, and quercetin as determined by HPLC, which might contribute directly to antioxidant activity (Chang et al., 2008). Flower extracts using different chromatographic techniques identified three different flavonoid glycosides, namely isorhamnetin-3-O-glucoside, isorhamnetin-3-O-rutinoside, and kaempferol 3-O-α-arabinoside (Ahmed et al., 2005). The identification of *O. dillenii* flavonoids from cladode segments includes isorhamnetin, kaempferide, kaempferol, quercetin, 3-*O*-methyl quercetin, isorhamnetin-3-*O*-rutinoside, and isorhamnetin-3-*O*-galactoside (Siddiqui et al., 2016).

The methanolic extract of *O. dillenii* cladodes was subjected to a vacuum liquid chromatographic technique, isolating two main fractions, opuntiol and opuntioside, respectively (Siddiqui

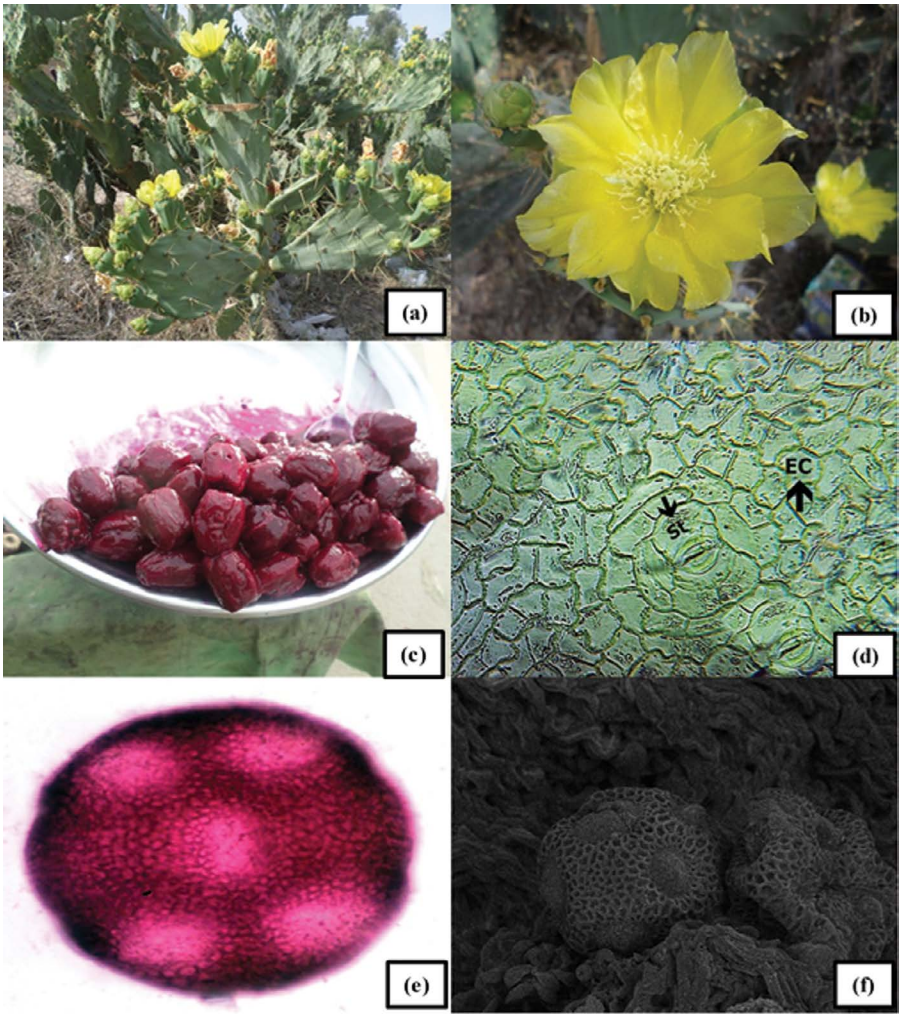

FIGURE 3.48 (a) *Opuntia dillenii* with stem segments, (b) flower, (c) edible fruits, (d) stem epidermis, (e) LM micrograph of pollen, (f) SEM view of pollen sculpturing.

et al., 2016). According to Qiu et al. (2002) organic compounds from cladode extracts (4-ethoxyl-6-hydroxymethyl-α-pyrone, kaempferol 7-O-beta-D-glucopyranosyl-(1 → 4)-β-D-glucopyranoside, and opuntioside I) were isolated.

The HPLC analysis of *O. dillenii* fruit (seeds) extract confined the polyphenols, such as ferulic acid, gallic acid, *p*-coumaric acid, and sinapinic acid (Chang et al., 2008). The high amount of phenolic compounds (gallic acid) contributed to the antioxidant activity of *O. dillenii* juice (Moussa-Ayoub et al., 2016). Cactus fruit was found to contain two polyphenols, vanilllic acid and gallic acid (Mishra, 2016). Three phenolic compounds from the fresh stem ethanolic extract of *O. dillenii* showed p-hydroxybenzoic acid, (E)-ferulic acid, and ethyl 3,4-dihydroxybenzoate, which were identified using comparison with T.L.C. and N.M.R. spectra (Qiu et al., 2002).

The seeds of *O. dillenii* are rich in oil, and the high amount of unsaturated fatty acids analyzed by GC–MS possesses potentially antioxidant activity (Liu et al., 2009). The composition of *O. dillenii* seed oil containing linoleic acid as dominating fatty acid followed by palmitic acid and stearic acid was present at a low percentage (Ghazi et al., 2013; Ghazi et al., 2015). Fatty acid analysis of

TABLE 3.3
Phytochemical Bioactive Compounds of *Opuntia dillenii*

Class of Compounds	Source (Plant Part Used)	Phytochemicals	Chemical Formula	Citations
Alkaloids	Cladode	Not mentioned	NA	Pooja and Vidyasagar (2016)
	Fruit	Not mentioned	NA	Pooja and Vidyasagar (2016)
	Fruit	Not mentioned	NA	Kumaar et al. (2013)
	Leaves	Not mentioned	NA	Akter et al. (2009)
	Flower	Not mentioned	NA	Kumar et al. (2014)
	Stem	Lunamarine	$C_{18}H_{15}NO_4$	Chinedu et al. (2017)
	Stem	Ribalinidine	$C_{15}H_{17}NO_4$	Chinedu et al. (2017)
	Powder of plant sample	Not mentioned	NA	Zeb et al. (2015)
Betalains	Fruit	Betacyanin	$C_{24}H_{26}N_2O_{13}$	Moussa-Ayoub et al. (2017)
	Fruit (Juice)	Betacyanin	$C_{24}H_{26}N_2O_{13}$	Moussa-Ayoub et al. (2016)
	Fruit (Juice)	Betaxanthins	$C_{18}H_{18}N_2O_6^{-2}$	Moussa-Ayoub et al. (2016)
	Fruit	Betacyanin	$C_{24}H_{26}N_2O_{13}$	Cejudo-Bastante et al. (2015)
	Fruit	Betaxanthins	$C_{18}H_{18}N_2O_6^{-2}$	Cejudo-Bastante et al. (2015)
	Fruit	Betanin (Betacyanin)	$C_{24}H_{26}N_2O_{13}$	Betancourt et al. (2017)
	Fruit	17-decarboxybetanin (Betacyanin)	$C_{23}H_{26}N_2O_{11}$	Betancourt et al. (2017)
	Fruit	Isobetanin (Betacyanin)	$C_{24}H_{26}N_2O_{13}$	Betancourt et al. (2017)
	Fruit	17-decarboxyisobetanin (Betacyanin)	$C_{23}H_{26}N_2O_{11}$	Betancourt et al. (2017)
	Fruit	6′-O-sinapoyl-O-gomphrenin (Betacyanin)	$C_{35}H_{36}N_2O_1$	Betancourt et al. (2017)
	Fruit	d6′-O-sinapoyl-O-isogomphrenin (Betacyanin)	$C_{35}H_{36}N_2O_{17}$	Betancourt et al. (2017)
	Fruit	2′-O-apiosyl-4-O-phyllocactin (Betacyanin)	$C_{32}H_{36}N_2O_{20}$	Betancourt et al. (2017)
	Fruit	5″O-E-sinapoyl-2′-apiosyl-phyllocactin (Betacyanin)	$C_{43}H_{46}N_20_{24}$	Betancourt et al. (2017)
	Fruit	Tryptophan-betaxanthin (Betaxanthins)	$C_{20}H_{19}N_3O_6$	Betancourt et al. (2017)
	Fruit	Tyrosine-betaxanthin (Betaxanthins)	$C_{18}H_{18}N_2O_7$	Betancourt et al. (2017)
	Fruit	Proline-betaxanthin (Betaxanthins)	$C_{14}H_{17}N_2O_6$	Betancourt et al. (2017)
	Fruit (Pulp)	Betanin	$C_{24}H_{26}N_2O_{13}$	Mishra (2016)
	Fruit (Juice)	Betacyanins	$C_{24}H_{26}N_2O_{13}$	Embaby et al. (2016)
	Fruit (Juice)	Betaxanthins	$C_{18}H_{18}N_2O_6^{-2}$	Embaby et al. (2016)
	Fruit (Peel/Pulp)	Betanin	$C_{24}H_{26}N_2O_{13}$	Chang et al. (2008)
	Fruit (Peel/Pulp)	Iso betanin	$C_{24}H_{26}N_2O_{13}$	Chang et al. (2008)
	Fruit	Betacyanins	$C_{24}H_{26}N_2O_{13}$	Kalegowda et al. (2015)
Carbohydrate	Seed (Powder)	Not mentioned	NA	Rayan et al. (2018)
	Seed (Powder crude fiber)	Not mentioned	NA	Rayan et al. (2018)
	Fruit	Not mentioned	NA	Abdallah (2008)
	Stem	Not mentioned	NA	Chinedu et al. (2017)
	Fruit	D-saccharose	$C_{12}H_{22}O_{11}$	Kalegowda et al. (2015)
	Fruit	D-fructose	$C_6H_{12}O_6$	Kalegowda et al. (2015)
	Fruit	D-glucose	$C_6H_{12}O_6$	Kalegowda et al. (2015)

(Continued)

TABLE 3.3 ***(Continued)***
Phytochemical Bioactive Compounds of *Opuntia dillenii*

Class of Compounds	Source (Plant Part Used)	Phytochemicals	Chemical Formula	Citations
Organic compounds	Seed (Powder)	2.2-diphenyl-1-picrylhydrazyl	$C_{18}H_{12}N_5O_6$	Rayan et al. (2018)
	Stem	p-hydroxybenzoic acid	$C_7H_6O_3$	Qiu et al. (2002)
	Stem	L-malic acid	$C_4H_6O_5$	Qiu et al. (2002)
	Stem	3,3-dimethyl-quercetin	$C_{17}H_{14}O_7$	Qiu et al. (2002)
	Stem	4ethoxyl-6-hydroxymethyl-α-pyrone	NA	Qiu et al. (2002)
	Stem	1-heptanecanol	NA	Qiu et al. (2002)
	Stem	kaempferol 7-Ob -D-glucopyranosyl-(1→4)b -D-glucopyranoside	NA	Qiu et al. (2002)
	Stem	3-O-methyl quercetin 7-Ob -D-glucopyranoside	NA	Qiu et al. (2002)
	Stem	kaempferol 7-Ob -D-glucopyranoside	NA	Qiu et al. (2002)
	Fruit	Resins	NA	Kumaar et al. (2013)
	Stem	Thiobarbituric acid	$C_4H_4N_2O_2S$	Chinedu et al. (2017)
	Stem	Oxalate	$C_2O_4^{-2}$	Chinedu et al. (2017)
	Flower	Kaempferol 3-Oα arabinoside	$C_{20}H_{18}O_{10}$	Ahmed et al. (2005)
	Cladode (Stem)	Opuntiol	$C_7H_8O_4$	Siddiqui et al. (2016)
	Cladode (Stem)	Opuntiol	$C_7H_8O_4$	Siddiqui et al. (2016)
	Cladode	Opuntiol	$C_7H_8O_4$	Saleem et al. (2005)
	Stem	Opuntiol	$C_7H_8O_4$	Qiu et al. (2002)
	Cladode (Stem)	Opuntioside	$C_{13}H_{18}O_9$	Siddiqui et al. (2016)
	Cladode (Stem)	Opuntioside	$C_{13}H_{18}O_9$	Siddiqui et al. (2016)
	Cladode	Opuntioside	$C_{13}H_{18}O_9$	Saleem et al. (2005)
	Stem	Opuntioside	$C_{13}H_{18}O_9$	Qiu et al. (2002)
Fatty acids	Seed	Linolenic acid	$C_{18}H_{30}O_2$	Liu et al. (2009)
	Seed	Palmitic acid	$C_{16}H_{32}O_2$	Liu et al. (2009)
	Seed	Linoleic acid	$C_{18}H_{32}O_2$	Liu et al. (2009)
	Stem	Lauric acid	$C_{12}H_{24}O_2$	Chinedu et al. (2017)
	Stem	Myristic acid	$C_{14}H_{28}O_2$	Chinedu et al. (2017)
	Stem	Heptadecanoic acid	$C_{17}H_{34}O_2$	Chinedu et al. (2017)
	Stem	Stearic acid	$CH_3(CH_2)_{16}COOH$	Chinedu et al. (2017)
	Stem	Arachidic acid	$C_{20}H_{40}O_2$	Chinedu et al. (2017)
	Stem	Oleic acid	$C_{18}H_{34}O_2$	Chinedu et al. (2017)
	Stem	Linoleic acid	$C_{18}H_{32}O_2$	Chinedu et al. (2017)
	Seed (Oil)	Linoleic acid	$C_{18}H_{32}O_2$	Ghazi et al. (2013)
	Seed (Oil)	Palmitic acid	$C_{16}H_{32}O_2$	Ghazi et al. (2013)
	Seed (Oil)	Stearic acid	$CH_3(CH_2)_{16}COOH$	Ghazi et al. (2013)
	Seed (Oil)	Linoleic acid	$C_{18}H_{32}O_2$	Ghazi et al. (2015)
	Seed (Oil)	Palmitic acid	$C_{16}H_{32}O_2$	Ghazi et al. (2015)
	Seed (Oil)	Stearic acid	$CH_3(CH_2)_{16}COOH$	Ghazi et al. (2015)
Phenolics	Fruit (Seed)	Gallic acid	$C_7H_6O_5$	Chang et al. (2008)
	Fruit (Seed)	Sinapinic acid	$C_{11}H_{12}O_5$	Chang et al. (2008)
	Fruit (Juice)	Gallic acid	$C_7H_6O_5$	Moussa-Ayoub et al. (2016)
	Fruit (Seed)	*p*-coumaric acid	$C_9H_8O_3$	Chang et al. (2008)
	Fruit (Seed)	Ferulic acid	$C_{10}H_{10}O_4$	Chang et al. (2008)
	Stem	(E)-ferulic acid	$C_{10}H_{10}O_4$	Qiu et al. (2002)

(Continued)

TABLE 3.3 *(Continued)*
Phytochemical Bioactive Compounds of *Opuntia dillenii*

Class of Compounds	Source (Plant Part Used)	Phytochemicals	Chemical Formula	Citations
	Fruit	Isoramnethin-3-glucuronide	$C_{22}H_{20}O_{13}$	Betancourt et al. (2017)
	Fruit	Quercetin-3-O-glucoside	$C_{21}H_{20}O_{12}^{-}$	Betancourt et al. (2017)
	Cladode	Not mentioned	NA	Pooja and Vidyasagar (2016)
	Fruit	Not mentioned	NA	Pooja and Vidyasagar (2016)
	Seed (Powder)	Not mentioned	NA	Rayan et al., 2018)
	Stem	Ethyl 3,4-dihydroxybenzoate	C9H10O4	Qiu et al. (2002)
	Stem	3,4-dihydroxybenzoic acid	$C_7H_6O_4$	Qiu et al. (2002)
	Fruit	Gallic acid	$C_7H_6O_5$	Mishra (2016)
	Fruit	Vanillic acid	$C_8H_8O_4$	Mishra (2016)
	Fruit (Juice)	Total phenolic content	NA	Embaby et al. (2016)
	Stem	Phenol	C_6H_5OH	Chinedu et al. (2017)
Flavonoids	Fruit	Flavanol glycosides	$C_{15}H_{10}O_3$	Moussa-Ayoub et al. (2017)
	Fruit (Seed)	Epicatechin	$C_{15}H_{14}O_6$	Chang et al. (2008)
	Fruit (Seed)	Catechin	$C_{15}H_{14}O_6$	Chang et al. (2008)
	Fruit (Seed)	Quercetin	$C_{15}H_{10}O_7$	Chang et al. (2008)
	Fruit (Juice)	Isorhamnetin-3-O-rutinoside	$C_{28}H_{32}O_{16}$	Moussa-Ayoub et al. (2016)
	Cladode	Not mentioned	NA	Pooja and Vidyasagar (2016)
	Fruit	Not mentioned	NA	Pooja and Vidyasagar (2016)
	Seed (Powder)	Not mentioned	NA	Rayan et al. (2018)
	Stem	Isorhamnetin-3-O-rutinoside	$C_{28}H_{32}O_{16}$	Qiu et al. (2002)
	Stem	Rutin	$C_{27}H_{30}O_{16}$	Qiu et al. (2002)
	Stem	Manghaslin	$C_{33}H_{40}O_{20}$	Qiu et al. (2002)
	Fruit	Not mentioned	NA	Kumaar et al. (2013)
	Leaves	Not mentioned	NA	Akter et al. (2009)
	Flower	Not mentioned	NA	Kumar et al. (2014)
	Stem	Anthocyanin	NA	Chinedu et al. (2017)
	Stem	Rutin	$C_{27}H_{30}O_{16}$	Chinedu et al. (2017)
	Stem	Kaempferol	$C_{15}H_{10}O_6$	Chinedu et al. (2017)
	Stem	Catechin	$C_{15}H_{14}O_6$	Chinedu et al. (2017)
	Powder of plant sample	Not mentioned	NA	Zeb et al. (2015)
	Flower	Isorhamnetin-3-Oβ -D-glucopyranoside	NA	Ahmed et al. (2005)
	Flower	Isorhamnetin-3-Oβ -D-rutinoside	NA	Ahmed et al. (2005)
Steroids	Stem	Opuntisterol	$C_{29}H_{50}O_2$	Jiang et al. (2006)
	Stem	Opuntisteroside	$C_{35}H_{60}O_7$	Jiang et al. (2006)
	Stem	6β-Hydroxystigmast-4-en-3-one	$C_{29}H_{48}O_2$	Jiang et al. (2006)
	Stem	Daucosterols	$C_{35}H_{60}O_6$	Jiang et al. (2006)
	Fruit	Not mentioned	NA	Pooja and Vidyasagar (2016)
	Fruit	Not mentioned	NA	Kumaar et al. (2013)
	Leaves	Not mentioned	NA	Akter et al. (2009)
	Flower	Not mentioned	NA	Kumar et al. (2014)
	Seed (Oil)	β-sitosterol	$C_{29}H_{50}O$	Ghazi et al. (2013)
	Seed (Oil)	Campesterol	$C_{28}H_{48}O$	Ghazi et al. (2013)
	Seed (Oil)	Fucosterol	$C_{29}H_{48}O$	Ghazi et al. (2013)
	Seed (Oil)	Stigmasterol	$C_{29}H_{48}O$	Ghazi et al. (2013)
	Seed (Oil)	β-sitosterol	$C_{29}H_{50}O$	Ghazi et al. (2015)
	Seed (Oil)	Campesterol	$C_{28}H_{48}O$	Ghazi et al. (2015)

(Continued)

TABLE 3.3 *(Continued)*
Phytochemical Bioactive Compounds of *Opuntia dillenii*

Class of Compounds	Source (Plant Part Used)	Phytochemicals	Chemical Formula	Citations
	Seed (Oil)	Fucosterol	$C_{29}H_{48}O$	Ghazi et al. (2015)
	Seed (Oil)	Stigmasterol	$C_{29}H_{48}O$	Ghazi et al. (2015)
Saponins	Cladode	Not mentioned	NA	Pooja and Vidyasagar (2016)
	Fruit	Not mentioned	NA	Pooja and Vidyasagar (2016)
	Leaves	Not mentioned	NA	Akter et al. (2009)
	Stem	Not mentioned	NA	Chinedu et al. (2017)
	Stem	Sapogenin	NA	Chinedu et al. (2017)
	Stem	Not mentioned	NA	Nougbodé et al. (2013)
	Powder of plant sample	Not mentioned	NA	Zeb et al. (2015)
Polysaccharides	Fruit	Rhamnose	$C_6H_{12}O_5$	Gao et al. (2015)
	Fruit	Xylose	$C_5H_{10}O_5$	Gao et al. (2015)
	Fruit	Mannose	$C_6H_{12}O_6$	Gao et al. (2015)
	Fruit	Glucose	$C_6H_{12}O_6$	Gao et al. (2015)
	Cladode (Stem)	Arabinose	$C_5H_{10}O_5$	Kalegowda et al. (2017)
	Cladode (Stem)	Galactose	$C_6H_{12}O_6$	Kalegowda et al. (2017)
	Cladode (Stem)	Rhamnose	$C_6H_{12}O_5$	Kalegowda et al. (2017)
	Cladode (Stem)	Xylose	$C_5H_{10}O_5$	Kalegowda et al. (2017)
	Cladode (Stem)	Glucose	$C_6H_{12}O_6$	Kalegowda et al. (2017)
	Fruit	Rhamnose	$C_6H_{12}O_5$	Kalegowda et al. (2017)
	Fruit	Arabinose	$C_5H_{10}O_5$	Kalegowda et al. (2017)
	Fruit	Galactose	$C_6H_{12}O_6$	Kalegowda et al. (2017)
	Fruit	Xylose	$C_5H_{10}O_5$	Kalegowda et al. (2017)
	Fruit	Glucose	$C_6H_{12}O_6$	Kalegowda et al. (2017)
	Fruit	Mannose	$C_6H_{12}O_6$	Kalegowda et al. (2017)
	Fruit	Galacturonic acid	$C_6H_{10}O_7$	Kalegowda et al. (2017)
	Fruit	Galacturonic acid	$C_6H_{10}O_7$	Kalegowda et al. (2015)
Tannins	Fruit	Not mentioned	NA	Pooja and Vidyasagar (2016)
	Flower	Not mentioned	NA	Kumar et al. (2014)
	Leaves	Not mentioned	NA	Akter et al. (2009)
	Fruit	Not mentioned	NA	Kumaar et al. (2013)
	Stem	Not mentioned	NA	Chinedu et al. (2017)
	Stem	Not mentioned	NA	Nougbodé et al. (2013)
	Powder of plant sample	Not mentioned	NA	Zeb et al. (2015)
Vitamin A	Stem	Not mentioned	NA	Amadi et al. (2017)
Vitamin B	Fruit	Vitamin B_1	$C_{12}H_{17}N_4OS+$	Abdallah (2008)
	Fruit	Vitamin B_2	$C_{17}H_{20}N_4O_6$	Abdallah (2008)
	Stem	Vitamin B_6	$C_8H_{11}NO_3$	Amadi et al. (2017)
	Stem	Vitamin B_3	$C_6H_5NO_2$	Amadi et al. (2017)
	Stem	Vitamin B_{12}	$C_{63}H_{88}CoN_{14}O_{14}P$	Amadi et al. (2017)
Vitamin C	Fruit	Ascorbic acid	$C_6H_8O_6$	Moussa-Ayoub et al. (2017)
	Fruit (Pulp)	Ascorbic acid	$C_6H_8O_6$	Medina et al. (2007)
	Fruit (Peel/Pulp)	Ascorbic acid	$C_6H_8O_6$	Chang et al. (2008)
	Fruit (Juice)	Ascorbic acid	$C_6H_8O_6$	Moussa-Ayoub et al. (2016)
	Fruit (Juice)	Ascorbic acid	$C_6H_8O_6$	Embaby et al. (2016)
	Fruit	Not mentioned	$C_6H_8O_6$	Abdallah (2008)
	Fruit	β-carotene	$C_{40}H_{56}$	Abdallah (2008)
	Stem	Not mentioned	$C_6H_8O_6$	Amadi et al. (2017)

(Continued)

TABLE 3.3 *(Continued)*
Phytochemical Bioactive Compounds of *Opuntia dillenii*

Class of Compounds	Source (Plant Part Used)	Phytochemicals	Chemical Formula	Citations
Vitamin E	Fruit	Not mentioned	NA	Abdallah (2008)
	Stem	Not mentioned	NA	Amadi et al. (2017)
	Seed (Oil)	γ-tocopherol	$C_{28}H_{48}O_2$	Ghazi et al. (2013)
	Seed (Oil)	γ-tocopherol	$C_{28}H_{48}O_2$	Ghazi et al. (2015)
Vitamin D	Fruit	Vitamin D_3	$C_{27}H_{44}O$	Abdallah (2008)
	Stem	Not mentioned	NA	Amadi et al. (2017)
Vitamin K	Stem	Not mentioned	NA	Amadi et al. (2017)
Amino Acids	Stem	Valine	$C_5H_{11}NO_2$	Amadi et al. (2017)
	Stem	Threonine	$C_4H_9NO_3$	Amadi et al. (2017)
	Stem	Isoleucine	$C_6H_{13}NO_2$	Amadi et al. (2017)
	Stem	Leucine	$C_6H_{13}NO_2$	Amadi et al. (2017)
	Stem	Lysine	$C_6H_{14}N_2O_2$	Amadi et al. (2017)
	Stem	Methionine	$C_5H_{11}NO_2S$	Amadi et al. (2017)
	Stem	Phenylalanine	$C_9H_{11}NO_2$	Amadi et al. (2017)
	Stem	Histidine	$C_6H_9N_3O_2$	Amadi et al. (2017)
	Stem	Arginine	$C_6H_{14}N_4O_2$	Amadi et al. (2017)
	Stem	Tryptophan	$C_{11}H_{12}N_2O_2$	Amadi et al. (2017)
	Stem	Aspartate	$C_4H_7NO_4$	Amadi et al. (2017)
	Stem	Proline	$C_5H_9NO_2$	Amadi et al. (2017)
	Stem	Glycine	$C_2H_5NO_2$	Amadi et al. (2017)
	Stem	Alanine	$C_3H_7NO_2$	Amadi et al. (2017)
	Stem	Tyrosine	$C_9H_{11}NO_3$	Amadi et al. (2017)
	Stem	Glutamate	$C_5H_9O_4N$	Amadi et al. (2017)
	Stem	Serine	$C_3H_7NO_3$	Amadi et al. (2017)
	Stem	Cysteine	C3H7NO2S	Amadi et al. (2017)
Glycosides	Cladode	Not mentioned	Not mentioned	Pooja and Vidyasagar (2016)
	Fruit	Not mentioned	NA	Kumaar et al. (2013)
	Flower	Anthraquinone glycosides	$C_{14}H_8O_2$	Kumar et al. (2014)
Terpenoids	Stem	Taraxerol (Triterpenoid)	$C_{30}H_{50}O$	Jiang et al. (2006)
	Stem	Fridelin (Triterpenoid)	$C_{30}H_{50}O$	Jiang et al. (2006)
	Fruit	Not mentioned	NA	Pooja and Vidyasagar (2016)
	Powder of plant sample	Not mentioned	NA	Zeb et al. (2015)
Phytosterols	Stem	β-sitosterol	$C_{29}H_{50}O$	Jiang et al. (2006)
	Stem	7-oxositosterols	$C_{29}H_{48}O_2$	Jiang et al. (2006)
Proteins	Seed (Powder)	Not mentioned	NA	Rayan et al. (2018)
	Fruit	Not mentioned	NA	Abdallah (2008)
	Stem	Not mentioned	NA	Chinedu et al. (2017)
Methoxy benzoic acids	Stem	Vanillic acid	$C_8H_8O_4$	Qiu et al. (2002)
Fat	Fruit	Not mentioned	NA	Abdallah (2008)
	Stem	Not mentioned	NA	Chinedu et al. (2017)
ABTS	Seed (Powder)	ABTS	$C_{18}H_{18}N_4O_6S_4$	Rayan et al. (2018)
Ethers	Seed (Powder)	Not mentioned	NA	Rayan et al. (2018)
Lipids	Stem	Methyl linoleate	$C_{19}H_{34}O_2$	Jiang et al. (2006)
Inositol Phosphates	Stem	Phytate	$C_6H_{18}O_{24}P_6$	Chinedu et al. (2017)

Note: "NA" indicates that information was not mentioned in reviewed literature.

(Chinedu et al., 2017) indicated the presence of eight fatty acids; myristic acid with the highest concentration, along with linoleic acid, heptadecanoic acid, and stearic acid, were the major fatty acids found in matured stems of *O. dillenii*.

The fundamental screening of phytochemical constituents in methanol extracts of flowers and leaves of *O. dillenii* revealed the existence of various steroids (Akter et al., 2009; Kumar et al., 2014). Steroids were also isolated from the stems of *O. dillenii* via by spectroscopic analysis (Jiang et al., 2006). The seed oil steroid fraction was composed of β-sitosterol, campesterol, stigmasterol, and fucosterol (Ghazi et al., 2015).

The polysaccharides derived from stem segments of *O. dillenii* show antidiabetic and hypolipidemic effects (Zhao et al., 2012). The *O. dillenii* fruit contains different polysaccharide fractions (glucose, mannose, rhamnose, and xylose) that were isolated (Gao et al., 2015). The cladodes were mainly composed of mucilage, which is a naturally occurring polysaccharide complex composed of arabinose, galactose, rhamnose, xylose, and glucose. The extracted samples of the fruit peel consist of galacturonic acid with neutral sugars viz., galactose, arabinose, rhamnose, xylose, mannose, and glucose (Kalegowda et al., 2017).

Amino acid is important parameter of plant profiles to estimate their potential for growth, resource-using efficacy, and attributes of food and feeding (Dahl-Lassen et al., 2018). Apart from their function during protein synthesis, they also form the building blocks of many other biosynthetic pathways and play a vital role during the process of signaling as well as in plant responses during stress conditions (Hildebrandt et al., 2015). The sample of *O. dillenii* analyzed by (Amadi et al., 2017) showed that essential amino acids are arginine and leucine had the highest concentration, whereas the most abundant non-essential amino acid are glutamate and aspartate.

The earlier studies of (Chinedu et al., 2017) reported alkaloids of two types, including lunamarine and ribalinidine. Carbohydrates include D-Saccharose, D-fructose and D-glucose (Kalegowda et al., 2015); the terpenoids reported were taraxerol and fridelin, while phytosterols included β-sitosterol and 7-oxositosterols (Jiang et al., 2006); the only saponin was sapogenin (Chinedu et al., 2017); and the glycosides were anthraquinone (Kumar et al., 2014). There were various other compounds such as methoxybenzoic acids, fats, A.B.T.S., ethers, lipid tannins, and inositol phosphates (Rayan et al., 2018).

The use of extracts from of fruit, stem cladodes, seeds, flowers, and rudimentary leaves of *O. dillenii* present diverse pharmacological properties like analgesic, antioxidant, antidiabetic, anti-obesity, anti-inflammatory, hypotensive, hypoglycemic, radical scavenging, anti-angiogenic, anti-allergenic, anti-carcinogenic, cardio-protective, cytotoxicity, hepatoprotective, antiviral, antiproliferative, antifertility, and antitumor activities (Table 3.4). The reported pharmacological properties found that only (20%) studies represent information with standard procedures whereas most previous published work (80%) lacks standard protocols with incomplete information about the preparation of herbal extract and their identification.

From evaluation of anti-diabetic efficacy in the literature, there is mainly focus on the advancements in the various natural polysaccharides (Wang et al., 2016). Many drugs of natural, plant-based origin have been used globally for the treatment of diabetes. Thus, natural drugs derived from plants provide a possibility for controlling diabetes (Balakrishnan et al., 2009; Jaiswal et al., 2009). The earlier findings stated that extract of cladodes, fruits, and flowers, of *O. dillenii* showed significant anti-diabetic activity in streptozotocin-induced diabetic rats during in vivo experiments.

Antioxidants occur naturally in plants, and their components provide rich sources of natural antioxidants; they play an important role in preservation of food through inhibition of oxidation processes (Shahidi & Zhong, 2015). The literature (Chang et al., 2008; Liu et al., 2009; Rayan et al., 2018) demonstrated that seeds of *O. dillenii* contribute to strong antioxidant potential. Other studies (Betancourt et al., 2017; Li et al., 2016) identified betacyanin and betaxanthin components in prickly pear fruit extracts that are considered to pose higher antioxidant capacity and sources of

TABLE 3.4
Pharmacological Activities of Different Extracts of *Opuntia dilleniid*

Study	Activity	Plant part Used / Extract	Method Used and Model organism	Dose (s)/Duration	Control		Active compound (s)	Minimal active concentration	Toxicity	Results
					+ive	–ive				
Siddiqui et al. (2016)	Analgesic	*O. dillenii*/ Cladode/ Methanol	In vivo/ Mice	100–350 mg/kg/7 days	NA	Acetic acid, formalin	NA	NA	Agitation, restlessnes, sedation, sensitivity to touch and sound, diarrhea, motor activity, gasping, mortality	Edible *O. dillenii* exhibited analgesic activity at both peripheral and central levels. Its methanol extract and fraction possess centrally mediated pain-relieving effects.
Zhao et al. (2012)	Hypolipidemic	*O. dillenii*/ Fresh cladodes/High fat emulsion	In vivo/Rat	100,200,400mg/kg/ 28days	Zhibituo	High fat emulsion diet	ODP-Ia	NA	NA	ODP-Ia is a natural plant drive drug, having effects like those of zhibituo tablets for hyperlipidemia treatment.
Zhao et al. (2011)	Antidiabetic	*O. dillenii*/ fresh cladodes/ethanol	In vivo /Mice	100,200,400mg/kg/ 21days	Gliquidone	Injection of STZ dissolved in citrate buffer	ODP-Ia	NA	NA	This aids in the recovery of tissue function and improves sensitivity of target cells to insulin, so it controls the metabolic activities and affects biochemical indicators.
Yang et al. (2013)	Antioxidant	*O. dillenii*/ NA/ Distilled water, ethanol	Invitro	NA	NA	NA	NA	NA	NA	Pharmacological tests showed that its crude polysaccharides had good antioxidant activity.
Gao et al. (2015)	Antidiabetic	*O. dillenii*/ Fruit/ Distilled water	In vivo/Rats	50,100,200mg/kg/day/ 28 days	Glibenclamide	Injection of STZ	Rhamnose, xylose, mannose, glucose	NA	NA	ODFP decreased water intake, food intake, urine production, organ weight, and blood glucose level.

(Continued)

TABLE 3.4 *(Continued)*
Pharmacological Activities of Different Extracts of *Opuntia dilleniid*

Study	Activity	Plant part Used / Extract	Method Used and Model organism	Dose (s)/Duration	Control		Active compound (s)	Minimal active concentration	Toxicity	Results
					+ive	−ive				
Chang et al. (2008)	Antioxidant	*O. dilleniid*/Fruit, seed, pulp/ Methanol	In vitro	NA	Catechin	NA	NA	NA	NA	Methanolic extract of seeds from ODHF had a marked activity in ORAC, TEAC and anti-LDL cholesterol peroxidation system in vitro.
Liu et al. (2009)	Antioxidant	*O. dillenii*/ Seeds/ Methanol	In vitro	NA	NA	NA	NA	NA	NA	*O. dillenii* seed oil may play important role as health promoting agent with antioxidant activity in human diets as well as providing valuable natural antioxidants for pharmaceutical industry.
Siddiqui et al. (2016)	Anti-inflammatory	*O. dillenii*/ Cladode/ Methanol	In vivo/ Mice	1 and 5 g/kg/ 7 days	Celecoxib, Indomethacin, Dexamethasone, NDGA	PLA_2, Arachidonic acid, TPA	NA	NA	NA	*O. dillenii* cladodes have anti-inflammatory properties via inhibition of arachidonic acid metabolites and cytokines.
Loro et al. (1999)	Analgesic and anti-inflammatory	*O. dillenii*/ Fruits/ Aqueous	In vivo/ Rats and mice	50,100,200, 400 mg/kg	Indomethacin	Carrageenan	NA	NA	NA	The aqueous extract of *O. dillenii* is endowed with central analgesic properties, associated with anti-inflammatory processes.

(Continued)

TABLE 3.4 *(Continued)*
Pharmacological Activities of Different Extracts of *Opuntia dilleniid*

Study	Activity	Plant part Used / Extract	Method Used and Model organism	Dose (s)/Duration	Control		Active compound (s)	Minimal active concentration	Toxicity	Results
					+ive	−ive				
Betancourt et al. (2017)	Antioxidant	*O. dillenii*/ Fruit/ Aqueous methanol	In vitro	NA	NA	Ascorbic acid	NA	NA	NA	*O. dillenii* is a rich source of betalain compounds. It also exhibits potent antioxidant activity against A.B.T.S. radicals strongly related to the folin-Ciocalteau reduction capacity.
Rayan et al. (2018)	Antioxidant	*O. dillenii*/ Seeds/ Ether	Invitro	NA	NA	NA	NA	NA	NA	Its seeds can be used as a useful and valuable raw material for snacks produced by extrusion cooking. Rice-based extrudates of *O. dillenii* seed powder may be an attractive source of appetizers with increased nutritional properties.
Saleem et al. (2005)	Hypotensive, toxicology, histopathology	*O. dillenii*/ Cladodes/ Methanol	In vivo/Rats, mice	10 mg-1000 mg/kg/ 15 days	NA	NA	Opontioside-I	NA	Hyperemia, red paws, crams, tail erection, exophthalmos, increased respirator depth, ataxia, decreased motor activity, loss of grip, corner sitting, hind limb abduction, chromaturia	Methanolic extracts of *O. dillenii* cladodes and Opontioside-I have been emerged as potent hypotensive agents.

(Continued)

TABLE 3.4 *(Continued)*
Pharmacological Activities of Different Extracts of *Opuntia dilleniid*

Study	Activity	Plant part Used / Extract	Method Used and Model organism	Dose (s)/Duration	Control		Active compound (s)	Minimal active concentration	Toxicity	Results
					+ive	–ive				
Abdallah (2008)	Hypoglycemic	*O. dillenii*/ Fruit juice	In vivo/ Rats	5 ml/kg/day/ 4 weeks	NA	Citrate buffer/ STZ injection	NA	NA	Islets of Langerhans in the pancreas tissue of diabetic rats treated with *O. dillenii* fruit juice were normal, but few cells showed necrosis and some cells contained pyknotic nuclei	The edible portion of *O. dillenii* haw fruit is very nutritious, a rich source of vitamins B1, B2, and C in addition to the minerals Fe, Zn, Cu, Cr, Mn, Ca, and Mg. This activity is also attributed to its antioxidant activity; therefore, it could be recommended to be ingested as fresh fruit to diabetic and hypercholesterolemic patients beside the usual therapy.
Qiu et al. (2002)	Antioxidant	*O. dillenii*/ Fresh stem/ aqueous Ethanol	In vitro	48 microg/ml	NA	NA	NA	NA	NA	The aqueous ethanolic extract from the fresh stems of *O. dillenii* showed potent scavenging activity.
Akter et al. (2009)	Antioxidant	*O. dillenii*/ Leaves/ Methanol	Invitro	1–500 microgram/ liter/10 min	NA	NA	Bioactive components	NA	They produce reactive peroxy nitrite, which leads to serious toxic reactions with biomolecules	The presence of reductants (i.e. antioxidants) in *O. dillenii* extract causes the reduction of the Fe^{3}+/ferricyanide complex to the ferrous form.
Kumar et al. (2014)	Antioxidant	*O. dillenii*/ Flowers/ Methanol	In vitro	10–500 microgram/ml	NA	NA	Flavonoids	NA	NA	In the antioxidant assay, the DPPH assay exhibited potent antioxidant abilities with IC_{50} of 58.7 µg/mL

(Continued)

TABLE 3.4 *(Continued)*
Pharmacological Activities of Different Extracts of *Opuntia dilleniid*

Study	Activity	Plant part Used / Extract	Method Used and Model organism	Dose (s)/Duration	Control		Active compound (s)	Minimal active concentration	Toxicity	Results
					+ive	−ive				
Bouhrim et al. (2018)	Hepatoprotective effect	*O. dillenii*/ Seed oil/ Petroleum ether	In vivo/ Rats	1 ml/kg/ 14 days	ODSO	CCl_4	Trichloromethyl and trichloromethyl-peroxyl	NA	It causes liver damage like that produced by viral hepatitis	ODSO has a significant hepatoprotective effect on rats rendered hepatotoxic by CCl_4. This effect has been represented by the improvement of the state of the enzyme marks related to hepatocellular damage, the metabolic and excretory function of the liver, and lipid peroxidation in the liver.
Bajaj and Gupta (2012)	Fertility suppression	*O. dillenii*/ Fresh plant sample/ Methanol	In vivo/ Male rats	50 mg/kg/ 30 days	NA	NA	NA	NA	Reduced reproductive potential of male rats	*O. dillenii* is a potential source for the development of an antifertility drug for males because of its anti-spermatogenic nature and reversible effect on reproductive organs and physiology.
Ghazi et al. (2015)	Antioxidant	*O. dillenii*/ Seed oil, fruit juice/ Organic solvent	In vitro	NA	NA	NA	NA	NA	NA	Fruit juices presented strong antioxidant activities more important than vitamin C. Oil pigments have 1.5 times higher antioxidant activity than ascorbic acid. Antioxidants have been reported as being protective against certain types of cancer and may also reduce the risk of cardiovascular and cerebrovascular events.

(Continued)

TABLE 3.4 *(Continued)*
Pharmacological Activities of Different Extracts of *Opuntia dilleniid*

Study	Activity	Plant part Used / Extract	Method Used and Model organism	Dose (s)/Duration	Control		Active compound (s)	Minimal active concentration	Toxicity	Results
					+ive	–ive				
Shah et al. (2016)	Hepatoprotective effect	*O. dillenii*/ Fruit/ NA	In vivo/ Male albino mice	0.2 ml/ 15 days	NA	Cadmium	Flavonoids	NA	NA	*O. dillenii* fruit extract possesses hepato-protective and hepato-lobular regenerative potential.
Li et al. (2016)	Antioxidant	*O. dillenii*/ Fruit/ Ethanol	In vitro	2.0ml	NA	NA	NA	NA	NA	T-ODP and O-ODP showed excellent antioxidant activity on DPPH radicals and good activity against hydroxyl radicals and superoxide radicals; ODP-Ia exhibited the highest antioxidant ability. It is a source of natural antioxidants and food supplement in the pharmaceutical and medical industries.
Ghazi et al. (2015)	Anti-inflammatory, antidiabetic	*O. dillenii*/ Flowers, fruit, stem/ Alcohol	In vivo/ Male albino rats	200 mg/kg/ 4 hours	Indomethacin, Novalgin	NA	NA	NA	NA	Anti-inflammatory effects expressed as a percentage of inhibition were 53.9 and 52.6 compared with that of indomethacin, which was 63.4. Analgesic activities were 95% and 92.2%, compared with 129.8% of Novalgin at the same dose

(Continued)

TABLE 3.4 ***(Continued)***
Pharmacological Activities of Different Extracts of *Opuntia dilleniid*

Study	Activity	Plant part Used / Extract	Method Used and Model organism	Dose (s)/Duration	Control		Active compound (s)	Minimal active concentration	Toxicity	Results
					+ive	–ive				
Ejaz et al. (2014)	Anti-angiogenic effect	*O. dillenii*/ Phylloclade/ Aqueous	Invitro/ Chicken eggs	50 mg/ml/ 6 days	PBS	NA	NA	NA	Application of OD caused substantial damage to secondary and tertiary blood vessels	Aqueous extract of OD in concentrations of 4%, 6%, 8%, and 10% were evaluated for anti-angiogenic potential by observing the effects on developing blood vessels of CAM. Aqueous extract of OD resulted in reduction of the CAM area with thinning of the secondary blood vessels and fading of tertiary blood vessels.
Zhao et al. (2011)	Antidiabetic effect	*O. dillenii*/ Cladodes/ Ethanol	In vivo/ Male mice	100–400 mg/kg/22 days	Gliquidone	Streptozotocin	NA	NA	NA	ODP-Ia showed significantly increased antioxidative ability in the liver. ODP-Ia prevented loss of blood calcium and increase in PUN concentrations in diabetic mice. ODP-Ia, an effective hypoglycemic ODP, can scavenge reactive oxygen species, thereby protecting liver tissue from peroxidation damage. Furthermore, it aids the recovery of tissue function and improves the sensitivity of target cells to insulin.

(Continued)

TABLE 3.4 ***(Continued)***
Pharmacological Activities of Different Extracts of *Opuntia dilleniid*

Study	Activity	Plant part Used / Extract	Method Used and Model organism	Dose (s)/Duration	Control		Active compound (s)	Minimal active concentration	Toxicity	Results
					+ive	–ive				
Li et al. (2014)	Antitumor effect	*O. dillenii*/ Whole plant/ Ethanol	In vitro	1.44–0.005 mg/ml/ 24–48 hours	NA	NA	Polysaccharides	NA	NA	The cactus polysaccharides inhibited proliferation of lung squamous carcinoma SK-MES-1 cells by inducing S phase arrest and triggering apoptosis. Insight into molecular mechanisms indicated that the cactus polysaccharides could significantly increase P53 and PTEN expression, which were negatively regulated cell cycles and induced apoptosis in the lung cancer cells.
Pavithra et al. (2015)	Antiproliferative activity	*O. dillenii*/ Fruit/ Alcohol	In vitro	NA	NA	NA	Betalains	NA	The treatment with pigment, pectin and pulp induced dose-dependent cytotoxicity	The pulp, red pigment, and pectin occurring in *O. dillenii* isolated in this study were checked for their pro-apoptotic activities. The pigments which are mainly composed of betalain (betacyanin and betaxanthin) and pectin induced apoptosis in EAC cell lines in a concentration-dependent manner with pigment having maximum activity.

Note: "NA" indicates that information was not mentioned in reviewed literature.

natural antioxidants and food supplement in the pharmaceutical industry. The extract prepared from *O. dillenii* leaves and flowers showed effective in-vitro antioxidant properties due to high content of flavonoids and phenols (Akter et al., 2009; Kumar et al., 2014).

The analgesic and anti-inflammatory properties are known for employing remedies containing phytochemicals and upholding the folklore uses of the plants (Popoola et al., 2016; Tadiwos et al., 2017). Some researches in previous studies found that methanolic extract of stem cladode and edible fruit of *O. dillenii* have anti-inflammatory and analgesic effects, which provides scientific validation of its traditional uses for the development of novel analgesics (Loro et al., 1999; Siddiqui et al., 2016).

The liver is a vital organ of the body, and it takes care of several functions, like the metabolic processes that is essential for life and detoxification of xenobiotics produced in the body (Ahmad et al., 2018b; Shah et al., 2016). *O. dillenii* seed oil has a significant hepatoprotective effect on rats, which has been represented by the improvement of the state of hepatocellular damage (Bouhrim et al., 2018). The data obtained suggests that pigment from alcoholic extract of *O. dillenii*, which was studied for antiproliferative activity (Kalegowda et al., 2015) was a promising agent for chemoprevention by DNA-induced apoptosis.

O. dillenii was previously studied for other pharmacological activities, including anti-hyperlipidemic activity (Zhao et al., 2012) and hypotensive activity of methanolic stem extracts in normotensive rats (Saleem et al., 2005). Fruit juice demonstrates the hypoglycemic activity in STZ-induced diabetic rats (Abdallah, 2008). Some other studies on *O. dillenii* include antifertility effects for the development of anti-spermatogenic drugs (Bajaj & Gupta, 2012). In vivo anti-angiogenic study has significant anti-cancer potential (Ejaz et al., 2014), and identification of polysaccharides has antitumor effects on lungs (Li et al., 2016).

In traditional systems of medicine, plants as an essential part of healthcare systems have been used as herbal medicine of prime importance for long periods of time and have been identified globally (Ahmad et al., 2018; Mohammadhosseini et al., 2019). Herbal preparations mostly comprises different plant parts such as leaves, stems, roots, fruits, seeds, flowers, bark, and whole plants. The effectiveness of indigenous knowledge of different plant materials have been recognized based on trial and error, as well as taste, smell, and optical observations (Tariq et al., 2015). Different plant parts, especially fruit and stem cladodes of *O. dillenii*, are used globally for different disease treatments (Table 3.5). In literature, fruit were reported as the most frequently used parts (15 reports; 40%), following by stem segments (13 reports; 34%), leaves and whole plants (eight reports; 20%), and flowers and spines (two reports; 6%) as shown in Figure 3.49. Paste 62% as a dominant administration mode was reported followed by decoction and juice 38% and in raw form 10%. The most frequently treated diseases were diabetes, whooping cough, gonorrhea, and gastric ulcer. According to previous researchers (Cejudo-Bastante et al., 2015; Chang et al., 2008; Kanwal et al., 2013; Tao et al., 2005), *O. dillenii* stems and fruits are used frequently in the treatment of different ailments such as decreasing cholesterol levels, whopping cough, gonorrhea, gastric ulcers, inflammation, and diabetes as folk medicine.

O. dillenii offers significant potential for enhancing food security and human nutrition in arid and semi-arid regions. This cactus species is remarkably resilient to harsh environmental conditions, making it a viable agricultural option where conventional crops might fail (El Hassania et al., 2024). Its edible pads and fruits are rich in essential nutrients such as vitamins C and A, calcium, potassium, and dietary fiber, contributing to improved nutritional intake in areas with limited food diversity. Moreover, the plant's low water and nutrient requirements align well with sustainable agricultural practices, reducing the strain on already-scarce resources. The ability of *O. dillenii* to thrive in desert climates can aid in stabilizing food supplies by providing a reliable source of nourishment despite climate uncertainties. However, its incorporation into local food systems requires careful management to address potential challenges such as invasive spread and land competition with native species. The adoption of *O. dillenii* as a food source represents a promising strategy for bolstering food security and nutritional health in vulnerable regions, contingent upon balanced implementation and ecological consideration.

TABLE 3.5
Traditional Medicinal Utilization of *Opuntia dillenii* in Local Communities

Region	Local name	Part used	Dosage form/Route of administration	Medicinal use and treatment of disease	Recipe	Reference(s)
Chagharzai Valley, Buner, Pakistan	Zaqoom	Phylloclade, fruit	N/A	Demulcent and expectorant. Fruit, fencing	N/A	Sher et al. (2011)
Malakand Pass Hills, Khyber Pakhtunkhwa, Pakistan	N/A	Fruit	Paste	Anti-inflammation, expectorant	N/A	Ali et al. (2018)
Palamalai Hill area, Salem District, Tamil Nadu, India	Chapathikalli	Fruits, leaves, stem	Syrup, poultice	Kanthari fruit is used as a refrigerant and used to treat gonorrhea, baked and given to treat whooping cough, and in the form of syrup is given to control spasmodic cough and expectoration. Milk juice is a purgative. Leaves are smashed up and applied as a poultice to reduce inflammation. Stem juice is applied on the body to reduce fever.	N/A	Kumudha and Yogeshwari (2016)
Kot Malakand Agency, Pakistan	Not mentioned	Not mentioned	Not mentioned	Diabetes	N/A	Sher (2011)
Ramnagar region from the Nainital District, Uttarakhand, India	Nagphani	Stem	N/A	Stem is used for lactation.	N/A	Bohra et al. (2017)
Allai Valley, Western Himalaya, Pakistan	Zaqoom	Phylloclade, fruits	Poultice, juice	Phylloclade's poultice is used for extracting guinea worms. Fruits are edible, demulcent, and expectorant. The ripe fruit juice is a useful remedy for asthma and whooping cough.	N/A	Haq (2012)
Nathia Gali, Khyber Pakhtunkhwa	Anaar phali	Fruit	N/A	Gastric ulcer, lowering cholesterol, diabetes, analgesic, anti-inflammatory, anti-spermatogenic	N/A	Haq et al. (2013)
District Kotli, Azad Jammu, and Kashmir, Pakistan	Thor	Fruit	Juice	The plant is carminative, diuretic, and cures inflammation. Juice is used to cure earaches. Fruit is used as a condiment.	N/A	Ahmad et al. (2012a)

(Continued)

TABLE 3.5 *(Continued)*
Traditional Medicinal Utilization of *Opuntia dillenii* in Local Communities

Region	Local name	Part used	Dosage form/Route of administration	Medicinal use and treatment of disease	Recipe	Reference(s)
Lower Dir, Pakistan	Zoqam	Stem	Paste, decoction (15–20 days)	Hypertension	N/A	Ahmad et al. (2015)
Tamil Nadu India	Sappathikali	Stem bark, fruit, entire plant	The fruit's paste is applied	Snake bite	N/A	Upasani et al. (2018)
Swabi, Pakistan	Zukam	N/A	N/A	For burning sensations, whooping cough, hepatitis, asthma, poison, fever, constipation, conjunctivitis, edema, leucorrhea, menorrhagia.	N/A	Qasim et al. (2016)
Shangla, Pakistan	Zoqam	Fruit	The fruit juice is extracted. A cup of this juice three times a day is taken	Diabetes	N/A	Sher et al. (2013)
Swat Valley, Northern Pakistan	Zuqam	Fruit	Unprocessed form	Diabetes, gastric ulcer, inflammation	N/A	Khan et al. (2015)
Lesser Himalayas	Nakh band	Fruits	Fresh fruits are peeled off and eaten raw	Diabetes, gastric ulcer, inflammation	N/A	Abbasi et al. (2013)
District Buner, North-West Frontier Province	Zuqam	Phylloclade, fruits	Phylloclade poultice and raw fruits are used	Phylloclade poultice is used for extracting guinea worms. The ripe fruit juice is a useful remedy for asthma and whooping cough.	N/A	Hamayun (2003)
Banda Daud Shah, District Karak, Pakistan	Papar	Whole plant	N/A	It is cultivated at the border of crop field to protect them from grazing animals.	N/A	Murad et al. (2013)

(Continued)

TABLE 3.5 *(Continued)*
Traditional Medicinal Utilization of *Opuntia dillenii* in Local Communities

Region	Local name	Part used	Dosage form/Route of administration	Medicinal use and treatment of disease	Recipe	Reference(s)
Southern India	Sappathikalli	Inner fleshy part of the stem	Two teaspoons of paste are taken once a day for 2–3 days early in the morning.	Healing wounds	The inner fleshy part of the stem is mixed with the leaf of the aloe vera and sugar. The mixture is ground into a paste and taken orally as well as applied topically on affected places to heal wounds.	Ayyanar and Ignacimuthu (2009)
Kani tribe in the Tirunelveli Hills, India	Sappathikalli	Stem	Paste (applied as tropical)	Healing wounds	N/A	Ayyanar and Ignacimuthu (2011)
Azad Jammu and Kashmir, Pakistan	Danda Thor	Leaves, fruit, aerial parts	Leaves are applied as paste. Fruit juice and latex from aerial parts are used.	Leaves' paste is used for anti-inflammatory purposes. fruit juice is used as a laxative, an expectorant, and against gonorrhea, hepatic congestion, asthma, whooping cough, and diabetes.	N/A	Rashid et al. (2015)
Madhupur, Tangail, Bangladesh	Narpanda siju	Latex spines	Spines are used as traditional needles	Cattle eye diseases Burst boil	N/A	Anisuzzaman et al. (2007)
Sagordighi, Netrokona, Bangladesh	Narpanda-siju	Stem latex	N/A	Stem latex is used in eye diseases of cattle.	N/A	Partha and Hossain (2007)

(Continued)

TABLE 3.5 ***(Continued)***
Traditional Medicinal Utilization of *Opuntia dillenii* in Local Communities

Region	Local name	Part used	Dosage form/Route of administration	Medicinal use and treatment of disease	Recipe	Reference(s)
Nagzira Wildlife Sanctuary, District Gondia (M.S.), India	Nagphani	Phylloclades and fruit	Poultice of phylloclades, juice of fruits	A poultice made from the phylloclades of this cactus is used for the extraction of guinea worms. The edible fruits are used as a demulcent and expectorant. Juice made from the ripe fruit is used in the treatment of asthma and whooping cough.	N/A	Koche (2008)
Silent Valley of Kerala, India	Sappathi kalli	Stem	Paste Decoction	Burns (Topical) Diabetes (Oral)	N/A	Yabesh et al. (2014)
Sirumalai Hills of Eastern Ghats, Dindigul District of Tamil Nadu, Southern India	Sappatikalli	Fruit	Decoction	Whooping cough	N/A	Alagesaboopathi (2012)
Yanadi tribe of Kavali, Nellore District, Andhra Pradesh, India	Nagajemudu	Whole plant	N/A	It is cultivated in front of the hut, as it is believed to protect against measles	N/A	Swapna (2015)
Palk Strait, coast of South India	Chapathikalli	Leaves, flowers	Paste	Abscesses, eye disease	Crush the flowers and leaves (remove the thorn), extract paste, and apply it on the area.	Ravikumar et al. (2011)
Chimur Tahsil, Chandrapur District, Maharashtra, India	Nagphani	Stem bark and pulp of leaves	N/A	Cough, elephantiasis, inflammation of thighs, and wounds	N/A	Bodele and Shahare (2015)
Irula tribes of Nellithurai Beat, Karamadai Range, Western Ghats, Tamil Nadu, India	Kalli	Whole plant	Decoction	Asthma, whooping cough, fever, constipation, ulcers, and liver complaints	N/A	Dhivya and Kalaichelvi (2016)

Note: "NA" indicates that information was not mentioned in reviewed literature.

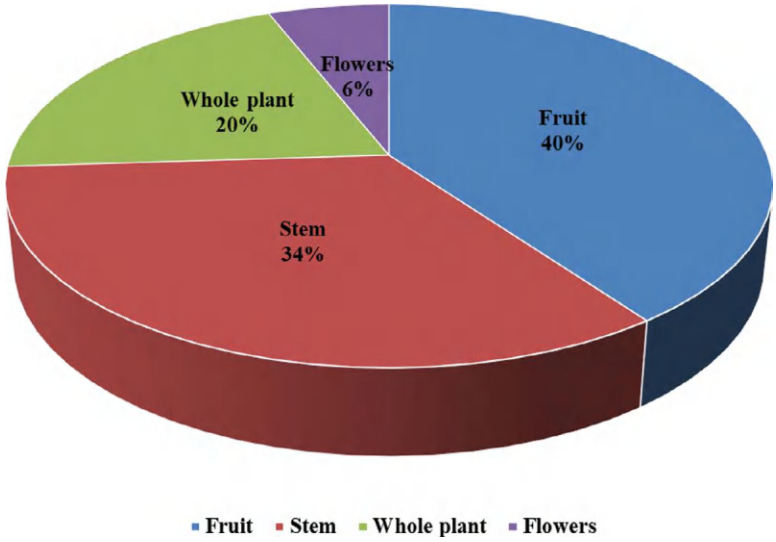

FIGURE 3.49 Graph showing percentage of different plant parts used of *Opuntia dillenii*.

3.3 ETHNOPHARMACOLOGICAL STATUS OF WEs OF THE CAPPARACEAE FAMILY

Pharmacolo-medicinal studies of the Capparaceae family reveal significant potential for species contributing to food security and human protein diets. Capparaceae, represented with the genera *Capparis* and *Cleome*, includes plants known for their nutritional and medicinal properties. The plants are rich in essential nutrients, including proteins, essential amino acids, and micronutrients vital for human health, and can help address protein deficiencies in developing regions. Traditional knowledge emphasizes the use of Capparaceae species in various indigenous diets, where they are utilized for their high protein content and potential therapeutic benefits. For example, *Capparis spinosa*, or caper bush, has been recognized for its edible parts, including the buds and fruits, which are rich in proteins and antioxidants. Moreover, *Cleome* species, often consumed in traditional diets, offer valuable proteins and essential fatty acids. Integrating these plants into modern food systems could enhance nutritional security by diversifying protein sources and promoting sustainable agricultural practices. The ethnopharmacological significance of Capparaceae species highlights their potential role in addressing global food security challenges, particularly in regions with limited access to diverse protein sources.

3.3.1 *Capparis decidua* Edgew (Forssk.)

C. decidua, a perennial woody plant from the Capparaceae family, thrives in subtropical and tropical regions (Figure 3.50). Known by numerous vernacular names such as Kari, Delha, Caper, Kair, Karyal, Hanbag, Karil, and Kabra, it is indigenous to desert and arid environments across the Indian subcontinent, Africa, and Saudi Arabia. This species is prevalent in dry, tropical regions of Africa, including Tibesti (West Chad), Sudan (excluding the extreme South), the Arabian Peninsula, Egypt, Iran, India, Jordan, Pakistan, and the Mascarene Islands (Abra & Ali, 2011). Its significance in traditional medicine is well-established across various medicinal systems. Historically, *C. decidua* has been utilized to treat a wide range of ailments, including rheumatism, asthma, cough, lumbago, toothache, pyorrhea, dysentery, liver infections, diarrhea, febrile conditions, cardiac issues, constipation, ulcers, piles, renal disorders, and skin diseases (Mann et al., 2013; Nazar et al., 2020).

C. decidua, a species from the Capparaceae family, is a medicinally and nutritionally significant wild plant commonly found in arid and desert regions, particularly in the Cholistan Desert of Pakistan.

FIGURE 3.50 *Capparis decidua.*

This plant is notable for its high content of valuable bioactive compounds and phenolic antioxidants, and is traditionally used in South Asian medicine systems, particularly for treating infectious diseases. Furthermore, *C. decidua* is recognized for its potential as a source of essential nutrients and minerals, enhancing its nutritional value. Plants with elevated levels of calcium and potassium, like *C. decidua*, are particularly valued for their contributions to both livestock feed and human consumption (Gull et al., 2015). *C. decidua* is a xerophytic shrub widely utilized in food products and traditional folk medicine. Various parts of the plant and its derivatives have been employed for many years due to their beneficial properties. However, the plant also contains toxic components, primarily volatile compounds, which exhibit significant insecticidal activity against a broad spectrum of insect pests. For desert-dwelling populations, *C. decidua* is particularly valuable, as its cultivation in barren lands provides a vital resource and sustenance in otherwise inhospitable regions (Upadhyay, 2013).

Alrasheid et al. (2018) conducted nutritional compositional studies that show that *C. decidua* fruits are rich in essential food components and nutrients necessary for the healthy growth of both adults and children. The fruits are particularly high in potassium, an important electrolyte that helps maintain fluid balance and regulate blood pressure. This nutritional value highlights the potential of *C. decidua* to encourage local communities to manage and preserve wild plant resources. Moreover, this research supports efforts to maintain biodiversity and promote the sustainable use of underutilized WE plants. *C. decidua* is a versatile plant that provides essential resources such as food (in the form of pickles and vegetables), fodder, fuel wood, and timber, making it crucial to the rural economy in arid regions. This medicinal plant's economic value plays a significant ecological role by offering vegetation cover, enhancing soil quality, preventing soil erosion, and supporting biodiversity (Kumar et al., 2005). Furthermore, it is used as a hedge. Despite its importance, *C. decidua* has received relatively little scientific attention, which limits its development and sustainable use. *C. decidua* primarily propagates through seeds and

root suckers in natural conditions. The plant begins to bear fruit around 5–6 years of age. Green, tender fruits, at a small pea size, are suitable for pickling and vegetable uses. To achieve optimal market prices, fruits should be harvested 7–10 days after setting, when they reach 5–8 mm in diameter, typically during March–April. Mature fruits are consumed fresh by local residents. A ripe fruit consists of 55% pulp by weight and contains 8.6% protein, 1.8% total sugars, 1.1% reducing sugars, 0.057% phosphorus (P), 1.026% potassium (K), 0.055% calcium (Ca), 0.055% magnesium (Mg), and 7.81 mg of ascorbic acid per 100 g (Mahla et al., 2013).

A paste made from the young leaves and branches of *C. decidua* is applied topically as a plaster to treat boils and swelling, and is used for its anti-inflammatory, astringent, stomachic, laxative, and antidotal properties against skin diseases. A decoction of the fresh twigs is consumed to address jaundice, while the fumigation of the stems is employed as an anti-rheumatic treatment. Moreover, the stems serve as a poultice for swelling, joint pain, and headaches. The roots are utilized for alleviating fever, rheumatism, and jaundice (Abdalrahman et al., 2016). Polyamines such as spermidine and spermine are known for their antioxidant, anti-allergenic, and anti-arteriosclerotic effects. Methanolic extracts of *C. decidua* seeds have been found to contain glucocapparin and the volatile antibacterial compound methyl isothiocyanate, both of which exhibit anticancer properties. Histopathological analysis has confirmed the hepatoprotective activity of these extracts. The seeds also show antibacterial activity attributed to isothiocyanate aglycon. While glucocapparin itself has limited antibacterial properties, its derivative, isothiocyanate aglycon, demonstrates significant antibacterial effects. *C. decidua* is a bush or small tree with leafless branches at certain stages of its life cycle, featuring pairs of straight, glabrous green spines. The plant bears red or yellow flowers on short lateral shoots, and the fruits are small, slightly beaked berries that turn red upon ripening. Moreover, a water-soluble alkaloid, 1-stachydrine, has been isolated from the flowers, fruit husk, fruit pulp, and root bark (Nehra et al., 2022; Pal et al., 2021).

3.3.2 *Capparis spinosa* L.

C. spinosa, commonly known as the caper, is a notable member of the *Capparis* genus within the Capparidaceae family (Figure 3.51). The *Capparis* genus comprises over 250 flowering species found across a variety of habitats, ranging from subtropical to tropical regions. The caper itself is a perennial shrub, characterized by its thorny stems and typically grows to a height of 0.3 to 1 meter. It is widely recognized by various names, with "caper" being most commonly used in English (Tlili et al., 2011). *C. spinosa* is a perennial plant renowned for its edible flower buds, known as capers, which are widely utilized in culinary applications for their distinctive tangy flavor. This hardy shrub is native to the Mediterranean region and thrives in arid, rocky soils, making it well-adapted to environments with minimal water. Capers are harvested from the bush's flower buds before they bloom and are typically pickled in vinegar or brined to enhance their unique taste. From a nutritional standpoint, capers are low in calories yet rich in essential vitamins and minerals. They are an excellent source of vitamin K, which plays a crucial role in bone health and blood clotting. Moreover, capers contain significant amounts of antioxidants, including flavonoids and polyphenols, which can help combat oxidative stress and inflammation in the body. They are also known for their high levels of dietary fiber, which supports digestive health. Beyond their health benefits, capers are a versatile ingredient in various dishes, providing both flavor and texture to Mediterranean, Middle Eastern, and Southern European cuisines (Nabavi et al., 2016).

C. spinosa is a perennial plant widely recognized for its aromatic properties. It commonly thrives along roadsides, on slopes, and in rocky or stony environments, showing a particular adaptability to arid and semi-arid regions. Wild populations of *C. spinosa* are found in countries around the Mediterranean Basin, extending to the Great Sahara in North Africa and into the dry areas of Western and Central Asia. The caper bush is well-suited to a semi-arid climate, requiring mean annual temperatures above 14°C and experiencing annual rainfall ranging from 200 mm (Rahnavard & Razavi, 2017). Various parts of *C. spinosa*, including its fruits and roots, have been employed as

FIGURE 3.51 *Capparis spinosa.*

traditional herbal remedies for their therapeutic effects on human ailments since ancient times. In ancient Egypt and Arabia, the roots of *C. spinosa* were utilized to treat liver and kidney disorders. The ancient Romans applied *C. spinosa* for the treatment of paralysis, while in Morocco, it was used to manage diabetes. In northern Pakistan, the root bark of *C. spinosa* has been traditionally used to treat conditions such as splenomegaly, mental disorders, and tubercular glands. Traditional Uighur medicine in China has utilized *C. spinosa* to manage rheumatoid arthritis and gout, whereas in Iran, it is used to treat hemorrhoids and gout (Zhang & Ma, 2018). Perennial caper plantations can enhance soil moisture retention over extended periods and support the sustainability of agroecosystems. The shrubs provide soil protection from direct sunlight, reducing soil temperatures and thus regulating the microclimate. Compared to other desert vegetation, caper plants exhibit high water use efficiency and an exceptional capability to access and absorb water from deeper soil layers, owing to their extensive root systems and high root-to-stem ratio (Chedraoui et al., 2017).

In Middle Eastern folk medicine, *C. spinosa* has been traditionally used to address a variety of health issues, including gastrointestinal disorders, spleen diseases, earaches, skin conditions, and kidney dysfunctions. Recent experimental and clinical research has explored the pharmacological properties of *C. spinosa*, revealing a broad spectrum of biological activities. These studies have highlighted its potential antioxidant, anti-inflammatory, anti-cancer, antimicrobial, and anti-diabetic effects (Sher & Alyemeni, 2010; Vahid et al., 2017). Caper seeds are recognized as a significant source of antioxidant compounds, making them valuable for the food and pharmaceutical industries due to their high phenolic content and potent antioxidant activity. They are also an accessible source of omega-6 fatty acids, and the oil extracted from these seeds is characterized as oleic-linoleic oil (Argentieri et al., 2012; Tlili et al., 2015).

The aerial parts of *C. spinosa* contain several key compounds, including cappariloside A, stachydrin, hypoxanthine, uracil, capparine A, capparine B, flazin, guanosine, 1H-indole-3-carboxaldehyde,

4-hydroxy-1H-indole-3-carboxaldehyde, kaempferol, thevetiaflavone, tetrahydroquinoline, rutin, kaempferol-3-glucoside, kaempferol-3-rutinoside, kaempferol-3-rhamnorutinoside, isorhamnetin 3-O-rutinoside, quercetin 3-O-glucoside, ginkgetin, isoginkgetin, sakuranetin, and glucocapparin. The roots primarily contain capparispine, cadabicine 26-O-β-D-glucoside, capparispine 26-O-β-D-glucoside, and stachydrine, while the seeds are rich in glucocapparin (Moufid & Farid, 2015). Traditionally, capers have been used to treat a variety of conditions, including headache, fever, convulsions, diabetes, toothaches, menstrual disorders, skin diseases, kidney and liver ailments, rheumatism, ulcers, hemorrhoids, and sciatica. Moreover, the fruit and leaves exhibit anti-diabetic effects; the fruit also demonstrates anti-obesity, cholesterol-lowering, and antihypertensive properties. Roots, fruits, stem barks, and shoots show antimicrobial activity, while leaves, roots, and fruits possess anti-inflammatory properties. The aerial parts of the plant are noted for their anti-hepatotoxic effects (Jalali et al., 2016; Shahrajabian et al., 2021).

C. spinosa has a long history of use in traditional phytomedicine. The polyphenols and other bioactive compounds extracted from this plant exhibit a range of therapeutic properties, positioning it as a promising candidate for further research aimed at enhancing health. *C. spinosa* is a valuable source of nutrients, with its consumable parts, buds and fruits, providing significant amounts of vitamins, protein, carbohydrates, and lipids. Furthermore, *C. spinosa* serves various other purposes, including as fodder, a source of honey, and an ornamental plant. Historically, it has been highly regarded as a medicinal plant with numerous therapeutic properties, deeply integrated into traditional medicine practices (Kdimy et al., 2022). Anti-diabetic activity is a notable feature of *C. spinosa* extracts. An ethanolic extract from the fruits of *C. spinosa* was evaluated for its anti-hyperglycemic and antihyperlipidemic effects in two distinct diabetic rat models, one induced by nicotinamide and the other by streptozotocin (Mishra et al., 2012). *C. spinosa* shows various pharmacological benefits. Earlier studies revealed that an ethyl acetate extract of *C. spinosa* has antioxidant properties. There is further exploration of its effects on doxorubicin-induced cardiac toxicity by analyzing cardiac cell health, oxidative damage, and mitochondrial function. *C. spinosa* demonstrated protective effects by reducing lactic dehydrogenase (LDH) and creatine kinase (CK) levels, enhancing the ability of myocardial tissue to neutralize free radicals, preventing lipid peroxidation, and improving antioxidant enzyme activity. Moreover, *C. spinosa* increased mitochondrial membrane potential and reduced reactive oxygen species (ROS) levels (Yu et al., 2017).

Archaeological evidence indicates that *C. spinosa* has been used since ancient times, with its beneficial effects on human health potentially dating back to the Stone Age. The earliest discovery of *C. spinosa* remains in China was found at the Yanghai Tombs, dating back approximately 2,800 years, located south of the Flame Mountains (Huoyan Shan) in Turpan, Xinjiang. This discovery also represents the earliest evidence of its edible use in eastern Central Asia. *C. spinosa* is a distinctive ingredient in global cuisine, with the primary edible parts being flower buds, fruits, and young shoots (including immature leaves). These parts are typically used as condiments to impart a unique flavor to a variety of dishes. Moreover, extracts of *C. spinosa* are utilized in food packaging to enhance the antioxidant and antimicrobial properties of the materials. With its distinctive taste, *C. spinosa* features in nearly 400 recipes, commonly used as a natural flavoring in sauces, salads, cold dishes, pasta, pizzas, cheeses, and meats. Most *C. spinosa*-based foods are salted or vinegared rather than consumed raw. During fermentation, *C. spinosa* develops a pungent flavor akin to mustard oil, attributed to its glucosinolates (Anwar et al., 2016; Memariani et al., 2020; Sun et al., 2023).

3.3.3 *Cleome brachycarpa* Vahl ex DC.

C. brachycarpa, commonly known as the desert spiderflower, is a resilient species native to arid regions, primarily found in parts of Africa and the Middle East (Figure 3.52). This herbaceous plant is notable for its distinctive inflorescence and robust structure, enabling it to thrive in harsh desert climates. Ethnobotanically, *C. brachycarpa* has garnered attention for its nutritional and medicinal properties. Traditionally, various communities have utilized the leaves, seeds, and roots of this

FIGURE 3.52 *Cleome brachycarpa.*

species as food sources, rich in essential vitamins and minerals. The plant foliage is often consumed as a green vegetable, providing a significant dietary supplement in regions where food scarcity is prevalent. In addition to its nutritional value, *C. brachycarpa* has been employed in traditional medicine systems, where it is believed to possess anti-inflammatory, analgesic, and antimicrobial properties. The bioactive compounds found in this species, including flavonoids and alkaloids, contribute to its therapeutic potential, supporting its use in treating ailments such as gastrointestinal disorders and skin infections. As interest in ethnomedicine and sustainable food sources grows, research into *C. brachycarpa* benefits is becoming increasingly important. This plant exemplifies the intersection of traditional knowledge and modern nutritional science, highlighting its potential role in promoting health and well-being in vulnerable desert communities. Further exploration of its uses could pave the way for innovative approaches to food security and natural medicine in arid environments.

C. brachycarpa, commonly referred to as punwar, is an ethnomedicinal plant indigenous to arid regions of Pakistan, thriving in the semi-arid to subtropical regions of Punjab, Sindh, Khyber Pakhtunkhwa, and adjacent areas. Often known as wild mustard or tick-weed, it plays a dual role in traditional practices, extensively utilized in conventional medicine and incorporated into culinary dishes, where its leaves and fresh branches are consumed (Rassouli et al., 2014). The seed pods are also popular for making pickles and local delicacies. Within the Ayurvedic medical framework, extracts from *C. brachycarpa* have been employed to address various health conditions, including diarrhea, malaria, hypertension, and snakebite (Nguyen et al., 2017). Notably, compounds such as visconoside, astragalin, kaempferol, quercetin, and kaempferitrin derived from the leaves have demonstrated hepatoprotective effects against CCl_4-induced liver toxicity. Moreover, citrus viscosa 3-O-(200-acetyl)-glucoside, another extract from this plant, is recognized for its antibacterial and anti-inflammatory properties, further highlighting the therapeutic potential of *C. brachycarpa* in

both culinary and medicinal contexts (Sumra et al., 2023). *C. brachycarpa* is recognized for its therapeutic applications in treating scabies, rheumatism, and inflammation, and is utilized as an analgesic for alleviating lower abdominal pain in traditional medicine systems across West Africa. Furthermore, it serves as fodder for sheep and goats. Research indicates that the essential oil derived from the aerial parts of *C. brachycarpa* contains significant components, including thunbergol, α-eudesmol, and elemol, which are considered major constituents of the oil (Joukar et al., 2023). Similarly, the presence of sesquiterpenes and flavonoids in *C. brachycarpa* enhances its antifungal, antibacterial, and antitumor properties, exhibiting significant cytotoxic effects. This plant demonstrates potent activity against plant pests and microbes, and it also possesses tranquilizing effects (Naeem et al., 2023).

The indigenous medicinal plant *C. brachycarpa* was examined for its antioxidant properties using three extraction methods: traditional soxhlet, microwave-assisted, and ultrasound-assisted techniques. The microwave-assisted extraction with methanol yielded the highest number of phytochemicals, recovering twice as much as the other methods, with an extraction efficiency of 370.57 ± 0.49 μg/mg. This method extracted notable amounts of polyphenols: Phenolics (74.17 ± 0.61 μg GAE/mg DW), flavonoids (65.46 ± 0.40 μg QE/mg DW), and tannins (55.97 ± 0.85 μg CE/mg DW). The methanolic extract showed strong antioxidant activity, with a DPPH radical scavenging percentage of 81.37 ± 0.28 and an IC50 of 0.30 mg/mL, comparable to Trolox. The study confirmed the significance of *C. brachycarpa* in traditional medicine due to its high polyphenolic content, suggesting its potential for further research and medicinal applications (Saleem et al., 2020). The leaves of *Cleome* are recognized for their effectiveness against scabies, mite-related skin diseases, and leucoderma (Khare, 2008). The plant exhibits antifungal, antibacterial, and anti-inflammatory properties. Moreover, the aerial parts of the plant contain sesquiterpenes and flavonoids, which contribute to its cytotoxic effects (Sarfaraz et al., 2018). Spectroscopic analysis has led to the isolation of cabralealactone, ursolic acid, and a new trinortriterpenoid dilactone, deacetoxybrachycarpone, from *C. brachycarpa*. The structures of cabralealactone, ursolic acid, and deacetoxybrachycarpone were elucidated. Furthermore, a new triterpenoid, cleocarbpone, was also isolated from *C. brachycarpa* (Sarfaraz et al., 2014).

3.4 WEs CUCURBITACEOUS SPECIES: THERAPEUTIC EFFECT ON HUMAN HEALTH

Cucurbitaceous species, commonly known as the gourd family, encompass a diverse array of plants including cucumbers, pumpkins, squash, and melons, many of which thrive in arid desert environments. Cucurbitaceae WEs not only provide essential nutrients but also exhibit significant therapeutic properties that can enhance human health. Rich in vitamins A, C, and various B vitamins, as well as minerals like potassium and magnesium, cucurbitaceous plants are valuable dietary components that support immune function, promote hydration, and aid in digestion. However, many species within this family contain bioactive compounds such as flavonoids, carotenoids, and cucurbitacins, which have been associated with anti-inflammatory, antioxidant, and potential anticancer effects. In traditional medicine, various parts of the plants, including seeds, fruits, and leaves, have been utilized for their purported health benefits, including blood sugar regulation, weight management, and digestive health. The sustainable and natural food sources grow, and understanding the therapeutic effects of these desert WEs offers promising avenues for enhancing nutrition and health in arid regions, where food security and accessibility remain critical challenges.

3.4.1 *Citrullus colocynthis* (L.) Schrad

C. colocynthis, commonly known as colocynth or bitter apple, is a perennial vine native to arid regions, particularly in North Africa and the Middle East (Figure 3.53). This drought-resistant plant thrives in sandy soil and is characterized by its lobed leaves and yellow flowers, which produce small, round fruits (Figure 3.54). Despite its name, the colocynth fruit is notoriously bitter and

FIGURE 3.53 *Citrullus colocynthis.*

FIGURE 3.54 Edible fruit of *Citrullus colocynthis.*

unpalatable when raw due to the presence of toxic compounds, particularly colocynthin. However, when properly processed, the fruit has been utilized as a traditional WFP source and herbal remedy. Indigenous communities have historically leveraged its nutritional potential, utilizing the seeds and dried fruit in various culinary applications. The ability of *C. colocynthis* to adapt to harsh desert environments makes it a vital resource for sustenance, showcasing the intricate relationships between local ecosystems and human survival strategies in arid landscapes. Understanding its properties and potential uses highlights the importance of biodiversity in food security (Edeoga et al., 2005). *C. colocynthis* is an herbaceous plant renowned for its rich nutrient profile, contributing significantly to overall well-being. As an underutilized fruit crop in arid regions, nearly all parts of this plant are recognized for their health benefits. The seeds, in particular, are a valuable source of oil and protein, boasting an excellent profile of fatty acids and amino acids. *C. colocynthis* is considered exceptional due to its unique chemical composition, which underpins both its nutraceutical and therapeutic properties. This shows higher potential for remedial applications, particularly when compared to the diverse array of medicinal plants within the botanical realm. Many species in this family are adapted to dry conditions, exhibiting resilience to wet environments, frost sensitivity, and poor soil quality (Bhasin et al., 2020).

In India, this drought-tolerant species is commonly found in hot, arid regions. It plays a significant role in traditional Indian medicine and can be easily propagated through both vegetative and generative reproduction during the summer months (Rani et al., 2017). Local populations utilize the plant to address various ailments, including boils, pimples, constipation, and joint inflammation. Moreover, *C. colocynthis* is employed to help manage conditions such as elevated glucose levels, joint pain, rheumatism, and abdominal enlargement. The plant is also used to treat urticaria, constipation, snakebites, stomach aches, and hepatitis, highlighting its diverse therapeutic applications in traditional healing practices (Kapoor et al., 2020). *C. colocynthis* is a desert plant known for its rich array of bioactive compounds, including essential oils, glycosides, flavonoids, alkaloids, and fatty acids. Medicinal plants, such as *C. colocynthis*, are recognized for their ability to enhance the immune system. The dried fruit pulp of this species has traditionally been utilized to address gastrointestinal disorders, including indigestion, gastroenteritis, and intestinal parasites (Li et al., 2022). The aerial parts and fruit of *C. colocynthis* contain various flavonoid glycosides, including quercetin and flavone-3-glucosides such as isovitexin, iso-orentine, and iso-orentine-3-methyl ether. Furthermore, the fruit is rich in a complex array of Cucurbitane-type triterpene glycosides, specifically colocynthoside A and B (Hameed et al., 2020).

The bitter apple, commonly referred to as colocynth, bitter cucumber, bitter melon, egusi melon, *C. colocynthis* is a wild perennial that thrives in arid regions worldwide. It possesses significant therapeutic, nutraceutical, and culinary potential (Heydari et al., 2016). The fruit of *C. colocynthis* is characterized by its bitter taste, spherical shape, smooth texture, and firm consistency, encased in a tough rind, containing approximately 200–300 seeds per gourd. This plant is utilized in the treatment of various ailments, including joint pain, leprosy, bronchitis, cancer, and mastitis. Various parts of the plant; leaves, flower petals, root system, fruit, fruit extract, seed residue, and seed pods can be used to formulate medicines and herbal products, as well as applications in the food industry. The moisture content of the ripe fruit is notably high, comprising over 90% of its total weight (Hussain et al., 2014; Rao & Poonia, 2023).

3.4.2 *Cucumis melo* L.

Cucumis melo, commonly known as melon, encompasses various cultivars, including cantaloupe and honeydew, which hold significant potential for food sustainability and medicinal applications (Figure 3.55). This species thrives in arid environments, making it an essential crop for regions facing water scarcity. Rich in vitamins A and C, melons contribute to dietary health while their high water content supports hydration in drought-prone areas. Moreover, traditional medicinal practices have utilized different melon parts: Seeds, flesh, and skin for their antioxidant and

FIGURE 3.55 *Cucumis melo.*

anti-inflammatory properties. The global food systems increasingly seek resilient and nutritious crops. *Cucumis melo* stands out as a versatile option, promoting both environmental sustainability and enhancing food security in vulnerable communities (Garcia-Mas et al., 2012). Its adaptability and health benefits position it as a vital resource for future agricultural practices. Melon, a member of the Cucurbitaceae family, is widely cultivated for its succulent fruits. The phenotypic and biochemical characteristics of melons vary significantly depending on the agroclimatic zones and local preferences (Endl et al., 2018). Over the past century, melon breeding has achieved significant advancements, and this progress is expected to continue. However, further research is necessary to uncover new genetic information related to genes that address the challenges posed by climate change (Kesh & Kaushik, 2021). Melon has a rich historical development in regions such as Iran, India, and China. It was commonly exchanged between the East and West along the Silk Road, facilitating its spread and cultivation across diverse cultures (Zhang et al., 2017).

Melon processing results in a significant amount of peels and seeds, which are noted for their higher concentrations of bioactive compounds compared to the pulp, including polyphenols, carotenoids, and oils (Gomez-Garcia et al., 2020). The fruit itself is recognized for its delicious flavor and high nutritional and medicinal properties. Bioactive compounds such as fatty acids, polyphenols, and carotenoids present in melons offer various health benefits. Historically, melon has been regarded as a natural therapeutic agent, providing preventive and curative effects against numerous chronic diseases, including aging, inflammation, and certain cancers (Rodríguez-Pérez et al., 2013). According to FAO data, global melon production exceeds 40 million ton annually, with Portugal and Mexico contributing approximately 57,000 and 594,000 ton, respectively (FAOSTAT, 2013). Melons include several commercially significant crops, featuring a wide range of botanical and horticultural types cultivated in temperate, subtropical, and tropical regions worldwide. Current melon varieties have been developed through human selection from wild melons, which originally produced small fruits with thin, bitter flesh. The high tendency for outcrossing in melons has resulted

in diverse botanical forms and intermediate types with various horticultural applications. Both fruit and vegetable melon varieties, particularly locally adapted landraces and wild types, possess favorable nutritional properties that can enhance human health, offering potential solutions for addressing chronic diseases through food and nutrition (Manchali et al., 2021; Napolitano et al., 2020).

The nutritional composition of melon by-products reveals valuable insights into their potential health benefits. Melon seeds exhibit a high protein content, with values ranging from 14.91 g to 36.3 g per 100 g, alongside substantial total fat content averaging around 30.83 g. In contrast, melon peels contain significant fiber, with total dietary fiber reaching 23.51 g, enhancing their nutritional profile for digestive health. Moisture content in seeds and peels is relatively low, indicating concentrated nutrients, while ash content varies, reflecting mineral composition. Moreover, soluble sugars in melon contribute to its energy value, with the highest content found in the seeds at 19.0 g. This diverse nutritional profile emphasizes the importance of melon by-products as a sustainable food resource with beneficial properties (Azhari et al., 2014; Mehra et al., 2015; Petkova & Antova, 2015; Raji & Orelaja, 2014; Silva et al., 2020).

3.4.3 *Cucurbita maxima* Duchesne

C. maxima, commonly known as the pumpkin or squash, is a member of the Cucurbitaceae family and plays a significant role as a food source in desert environments (Figure 3.56). Adapted to arid conditions, this species thrives in areas with limited water availability, making it a vital crop for food security in harsh climates. Rich in essential nutrients, including vitamins A and C, fiber, and antioxidants, *C. maxima* not only provides sustenance but also supports overall health. Its versatile culinary applications from soups to desserts make it a staple in various cuisines. The seeds offer a source of healthy fats and protein, enhancing its value as a complete food resource. As climate change poses challenges to traditional agriculture, *C. maxima* stand out as one of the best options

FIGURE 3.56 *Cucurbita maxima.*

for sustainable food production in desert regions. Pumpkin is a valuable vegetable with significant potential as both a medicinal and functional food. All parts of the pumpkin, its peel, flesh, and seeds, are rich sources of phytochemicals and minerals. These components are nutritionally important due to their high content of total phenolics, flavonoids, total carotenoids, and essential macro- and microelements. The organic waste produced during pumpkin processing can be effectively repurposed in various food products to create functional and medicinal foods. Pumpkin seeds are particularly noted for their high zinc content, which garnered attention during the COVID-19 pandemic for its role in oxidation processes and enzyme activation within the body, highlighting the importance of zinc in supporting immune function (Hussain et al., 2021).

Pumpkin fruit exhibits antidiabetic activity, with studies evaluating its hypoglycemic and hypolipidemic effects. Extracts derived from pumpkin have also been tested for antimicrobial properties, yielding positive results that demonstrate the presence of antimicrobial agents capable of inhibiting the growth of disease-causing microbes (Badr et al., 2011). Due to its beneficial health effects, research has primarily concentrated on the fatty acid (FA) content and tocopherol composition in pumpkin seed oil. Conversely, other lipid components, such as sterols, alcohols, and phenolic acids, have been studied to a lesser extent, similar to investigations conducted on other food matrices, to identify specific markers characteristic of different plant varieties (Montesano et al., 2018). Pumpkin is a plant rich in antioxidants, including carotenoids, tocopherols, phenolic acids, and flavonols. It is widely cultivated across Europe, Asia, South America, North America, and Africa, with annual production estimated to exceed 20 million ton. This vegetable is a valuable dietary component, as its pulp is abundant in carotenoids, while its seeds provide a source of unsaturated fatty acids. Although less commonly used, pumpkin flowers and leaves are also edible. The pulp can be consumed both raw and processed, featuring in various forms such as cooked dishes, compotes, jams, purees, and juices (Kulczyński et al., 2020; Muruganantham et al., 2016).

3.4.4 *Luffa cylindrica* (L.) M.Roem

L. cylindrica, commonly known as the sponge gourd or luffa, is a versatile plant valued not only for its culinary applications but also for its medicinal properties (Figure 3.57). This tropical vine, belonging to the Cucurbitaceae family, is primarily cultivated for its fibrous fruit, which is often dried and used as a natural sponge. In culinary contexts, the young fruits are consumed as vegetables, rich in vitamins A and C, and possess antioxidant and anti-inflammatory properties. *L. cylindrica* has been utilized in traditional medicine for its potential health benefits, including digestive support and detoxification. Its ingredients are unique in texture, and mild flavor can enhance various sweet dishes, making it a promising candidate for innovative culinary creations that blend nutrition and taste (Adeniyi et al., 2023). The fruit of *L. cylindrica*, commonly known as sponge gourd, is a forest product found in various countries and belongs to the Cucurbitaceae family. The young fruits of *L. cylindrica* are edible and contain a range of bioactive compounds, including phenolics, flavonoids, triterpenoids, and ribosome-inactivating proteins, which are utilized for their medicinal properties. This plant is widely cultivated in Asia and Africa and serves as a valuable source of natural fibers for composite material development. The composition of *L. cylindrica* includes approximately 57–74% cellulose, 14–30% hemicellulose, and 1–22% lignin, along with 0–12.8% of other components such as extractives and ashes (Adeyanju et al., 2021; Manikandaselvi et al., 2016).

It contains a variety of phytochemicals, including chlorophylls, carotenoids, oleanolic acid, saponins, and triterpenoids. Saponins are a diverse group of chemically complex compounds that can be categorized into three major groups based on their aglycone structure, which may include steroidal and steroidal alkaloid forms (Vellapandian, 2022). *L. cylindrica* is also commonly referred to as vegetable sponge or natural sponge and is a lignocellulosic material readily available in nature. Its versatility allows it to be utilized in various applications, ranging from personal hygiene products to biotechnological tools in medical science. Furthermore, *L. cylindrica* features a well-developed

FIGURE 3.57 *Luffa cylindrica.*

polymer matrix characterized by a cellulosic network structure, which is derived from the loofah fruit after the peel and seeds have been removed (Salimi et al., 2021; Schio et al., 2022). The immature fruit of *L. cylindrica* resembles zucchini in both taste and texture, offering a mild, slightly sweet flavor with juicy, tender flesh. Like other members of the Cucurbitaceae family, this fruit is nutritionally rich, making it an excellent source of carbohydrates, vitamins, and minerals (Gorman et al., 2024). *L. cylindrica* can be grown in a variety of climates worldwide, yet it holds significant economic, cultural, and culinary importance in countries such as China, India, Southeast Asia, and Brazil. In Asian cuisine, the immature fruit is particularly valued for its ability to absorb and retain liquids, and it is renowned for its capacity to take on the flavors of any dish it is incorporated into, similar to tofu (Rolnik & Olas, 2020; Zhou et al., 2022).

L. cylindrica contains secondary metabolites such as saponins, glycosides, and flavonoids (Zhang et al., 2020). Most of these non-nutritive compounds and their associated health benefits are concentrated in the peel and fruit of the luffa are diminished when the fibrous network is extracted for use as an exfoliator. Although the seeds are usually removed and discarded during production, they have been historically utilized in traditional medicine (Chaubey et al., 2022; Stright et al., 2024). Commonly known as "tori", this vegetable enjoys special popularity among local Asian communities. It is an herbaceous annual climber that grows wild in Africa but is widely cultivated and naturalized in tropical and subtropical regions. The young fruits of the plant can be consumed either fresh or cooked as a vegetable. In addition to the fruit, the leaves are also utilized as a vegetable. The seeds, which are edible after roasting, can be processed to produce edible oil (Khan et al., 2020a). *L. cylindrica* seed oil is incorporated into various cosmetic formulations, including sunscreens, sunless tanning products, anti-aging treatments, facial moisturizers, body oils, and facial cleansers. This is due to its antifungal, anti-inflammatory, and antitumor properties, which inhibit the

synthesis of specific proteins and are regarded as cytotoxic to skin cancer cells (Anaun & Ogundele, 2021). Traditionally, *L. cylindrica* has been utilized to address a range of health issues, including asthma, intestinal worms, sinusitis, chronic bronchitis pain, carbuncles, abscesses, inflammation, heat rashes, bowel or bladder hemorrhage, hemorrhoids, jaundice, menorrhagia, hematuria, leprosy, and splenopathy. It also serves as an antiseptic, emmenagogue, and carminative. The fruit of *L. cylindrica* is particularly noted for its effectiveness in clearing phlegm and exhibiting antipyretic properties. Additionally, it has been used to manage hyperglycemia and cataracts, and it has demonstrated anti-emetic, anti-inflammatory, and antimicrobial effects. Research on the leaves has focused on their potential anti-cancer, hepatoprotective, and anthelminthic actions (Singh & Vellapandian, 2023).

3.4.5 *Momordica charantia* L.

M. charantia, commonly known as bitter melon, is a resilient plant thriving in arid desert regions (Figure 3.58), making it a valuable nutritional source for local communities. This climbing vine produces fruit rich in vitamins A and C, essential minerals, and bioactive compounds, offering potential health benefits, such as improved glycemic control and antioxidant properties. In arid environments, where food security is often compromised, bitter melon's drought-resistant nature

FIGURE 3.58 *Momordica charantia.*

allows it to flourish with minimal water requirements. Its leaves, fruit, and seeds can be utilized in various culinary applications, contributing to dietary diversity and nutrition. Furthermore, the cultivation of *M. charantia* supports local agricultural practices, enhancing resilience to climate change while promoting sustainable food sources in harsh conditions. *M. charantia* is cultivated across Asia, East Africa, and certain regions of South America. The cultivar prevalent in China typically measures 20–30 cm in length, featuring an oblong shape with bluntly tapering ends, a light green hue, and an undulating surface. In contrast, the variety cultivated in India is smaller and has pointed ends. Historically, this plant has been utilized in traditional medicine to address various health issues, including diabetes, chronic fever, joint pain, skin disorders, and digestive ailments (Bora et al., 2023; Hossain et al., 2020). Bitter gourd is often unaccepted due to its distinct bitterness; however, the fruit is rich in essential nutrients. The entire plant contains over 60 phytochemicals that exhibit activity against more than 30 diseases, including cancer and diabetes. Recently, there has been a growing interest in incorporating bioactive compounds derived from bitter gourd into functional foods and beverages. Techniques such as nanoencapsulation and innovative green extraction methods can enhance both the yield and quality of these extracted compounds, improving their stability for use in food products.

In various Asian cuisines, the fruits, flowers, and young shoots of bitter gourd are utilized as flavoring agents. The fruits are often cooked with other vegetables, particularly in soups, to impart a subtle bitter flavor. In Indian cooking, however, the fruits are typically treated through blanching, parboiling, or soaking in salt water to mitigate their bitterness before use (Saeed et al., 2018). Bitter gourd is frequently overlooked due to its bitter taste, despite being a rich source of essential nutrients. It boasts a higher nutritional value than other cucurbits such as squash, pumpkin, cucumber, and zucchini, attributed to its elevated mineral and vitamin content. The fruit is abundant in vitamins, including vitamin A, vitamin E, thiamine, riboflavin, niacin, folate, and vitamin C. Moreover, it contains significant levels of potassium, iron, calcium, magnesium, phosphorus, and zinc, along with a substantial amount of dietary fiber (Nagarani et al., 2014). Bitter gourd is among the few edible fruits that contain conjugated α-linolenic acid in its seeds. Additionally, its seed oil has been reported to contain a long-chain polyunsaturated fatty acid (PUFA), α-eleostearic acid (Gayathry & John, 2022). Bitter gourd is also utilized in brewing and is consumed in various forms, including soups and fried dishes, across different regions of the world. Moreover, many people enjoy dried bitter gourd fruits as a tea (Mohammed et al., 2023). *M. charantia* is particularly noted for its anti-diabetic compounds, including charantin, vicine, polypeptide-p, and ribosome-inactivating proteins. Consequently, it has been primarily employed as a dietary intervention for hyperglycemia, as well as for regulating body weight and lipid metabolism (Li et al., 2020).

M. charantia is an annual herb that thrives in tropical and subtropical regions. This plant contains a range of bioactive compounds, including glycosides, saponins, proteins, alkaloids, triterpenes, and steroids. The polysaccharide extracted from *M. charantia* is a complex bioactive polysaccharide characterized by a diverse monosaccharide composition and various biological activities (Cui et al., 2020). *M. charantia* is recognized for its dual role as both a medicinal and food homology plant, offering significant pharmaceutical and nutritional benefits. Polysaccharides, which are carbohydrate polymers linked by glycosidic bonds, represent one of the key functional components of *M. charantia*. Recently, *M. charantia* polysaccharides have gained worldwide popularity as functional ingredients, commonly used in the preparation of tea, milk, yogurt, and a variety of beverages (Zheng et al., 2023). Notably, the seeds and fruits of *M. charantia* are high in protein, meeting the amino acid requirements established by the WHO for preschool children. This plant has garnered significant attention in biological and biomedical research due to its remarkable biological activities, particularly its antidiabetic and hypoglycemic effects. *M. charantia* is typically available in one of four forms: Fruit juice, whole fruit, freeze-dried powder, or capsules. These preparations often consist of crude extracts obtained using water, ethanol, or methanol, with effective monomer components extracted from the fruit, seeds, and leaves. As diabetes mellitus remains a major global health issue, several bioactive compounds derived from *M. charantia* may offer therapeutic benefits

by inhibiting α-glucosidase and α-amylase, activating AMPK, JNK, and Akt signaling pathways, enhancing PTP1B activity, and reducing the formation of advanced glycation end-products (Xu et al., 2022).

3.4.6 *Mukia maderaspatana* (L.) M.Roem

M. maderaspatana, commonly known as the Indian cucumber, is a resilient plant thriving in arid desert regions (Figure 3.59). With its high nutritional value and adaptability, it presents a promising food source for communities facing food scarcity. Rich in vitamins, minerals, and antioxidants, *M. maderaspatana* offers essential nutrients that can help combat malnutrition, particularly in environments where conventional crops struggle to grow. The plant's ability to tolerate drought and poor soil conditions makes it an ideal candidate for cultivation in harsh climates. Moreover, its edible fruits and leaves can be incorporated into various traditional dishes, enhancing dietary diversity. As climate change continues to impact food security globally, *M. maderaspatana* emerges as a sustainable nutritional option, promoting both health and resilience among vulnerable populations in arid landscapes (Sujata, 2020). The edible components of *M. maderaspatana* are commonly utilized in various dishes and savory preparations across south India. Both the leaves and roots, known as musumusukkai, are consumed as vegetables, while the ripe and unripe fruits are also eaten. Additionally, the aerial parts of the plant are utilized in traditional medicine to treat conditions such as vertigo and biliousness (Kumar et al., 2022). *M. maderaspatana* has traditionally been used in various forms to address a range of ailments, including colds, coughs, wounds, piles, toothaches, throat infections, antifertility issues, diabetes, liver disorders, and other ethnopharmacological

FIGURE 3.59 *Mukia maderaspatana*.

applications. Notably, hydroalcoholic leaf extract of *M. maderaspatana* has shown promise as an anti-cancer agent, demonstrating significant cytotoxic effects on HepG2 cells. Cell cycle analysis and annexin-V/PI assays indicated that the hydroalcoholic leaf extract effectively halted cell progression at the G2/M phase and induced apoptosis in HepG2 cells (Kumar et al., 2024b).

The bioactive phytochemicals in *M. maderaspatana* contribute to a reduced risk of cardiovascular diseases. Beyond cardiovascular health, the plant is also utilized in the treatment of cancer, obesity, diabetes, and allergic conditions. As a leafy vegetable, *M. maderaspatana* demonstrates both anti-diabetic and vasoprotective properties (Sujeethasai, 2020). This plant is recognized for its immunomodulatory activities and is frequently employed in the treatment of hepatic disorders (Nirmal et al., 2020). Phytochemical analysis of *M. madrespatana* has revealed the presence of phenolic compounds, tannins, flavonoids, alkaloids, and saponins. These phytochemical constituents act as potent reducing agents, primarily due to their abundant hydroxyl (OH) groups, which contribute to their significant antioxidant activity (Samad et al., 2020). The leaves of *M. maderaspatana* hold significant value in both Siddha and Ayurvedic medicine. Traditional medicinal practices suggest that the leaves and tender shoots possess a range of therapeutic properties, including aperient, diuretic, stomachic, antipyretic, antiflatulent, antiasthmatic, antitussive, antihistaminic, and antibronchitic effects, as well as expectorant activity (Saravanan et al., 2016). Leaf tea is used to help alleviate jaundice, while mupatena tea, made from extracts of the leaves and bark, is reported to serve as an effective decongestant and remedy for cough, cold, and flu symptoms (Gomathy et al., 2015). Rural desert communities prepare a cooked infusion of the leaves from both species, often combined with spices, to alleviate cold symptoms and throat pain. Decoctions made from the leaves of *M. maderaspatana* have been employed in the treatment of various conditions, including adenitis, piroplasmosis, theileriasis, plague, anthrax, rabies, mental disorders, and anaplasmosis (Chitra et al., 2015). The leaves of *M. maderaspatana* are rich in protein, fiber, iron, calcium, and vitamin C. Their potential use as a diuretic, anti-anemic, and antioxidant in patients can be attributed to their substantial mineral content, which includes calcium (5.13%), magnesium (3.19%), flavonoids (2.56 mg/kg), and manganese (14.20 ppm) (Sheeja et al., 2022).

Eugenol is the primary compound identified in the whole plant of *M. maderaspatana*, which is utilized in pharmacological research. Although saponins are typically classified as antinutrients, they are also thought to have beneficial effects on human health, particularly in cholesterol regulation. Thus, the presence of these compounds in this plant indicates its potential medicinal value (Gomathya et al., 2012). In Ayurveda, *M. maderaspatana* is utilized for a range of therapeutic purposes, including the relief of toothache and flatulence, as well as serving as an expectorant and sudorific. Additionally, some traditional medical practitioners recommend leaf tea from this plant for the alleviation of jaundice. Furthermore, our previous findings indicated that the consumption of *M. maderaspatana* leaf tea significantly reduced blood pressure, enhanced blood antioxidant capacity, and decreased glycoprotein levels in patients with hypertension (Raja et al., 2007).

3.5 NUTRITIONAL ASPECTS OF DROUGHT-RESISTANCE RHAMNACEOUS WEs

Desert species within the Rhamnaceae family, such as *Ziziphus* species, offer significant nutritional benefits that are critical for sustaining populations in arid environments. The plants have evolved unique adaptations that not only enable them to thrive under extreme conditions but also make them valuable sources of essential nutrients. Rich in vitamins, minerals, and bioactive compounds. Rhamnaceae edibles species contribute to dietary diversity and food security in regions where conventional agricultural practices may be limited. For instance, the fruits of *Ziziphus* are known to be rich in antioxidants, dietary fiber, and important micronutrients, promoting overall health and well-being (Asfaw et al., 2023). Moreover, the leaves provide vital forage for livestock, enhancing protein availability in pastoral communities. The cultivation and consumption of these

drought-resistant species can play a vital role in alleviating malnutrition, particularly in rural areas facing food scarcity. Moreover, their resilience to climate variability positions them as a sustainable resource in the face of global environmental challenges. As Rhamnaceae species as indigenous and sustainable food sources grow, understanding the nutritional aspects of Rhamnaceous WEs is essential for developing strategies to improve health outcomes and ensure food security in arid regions (Mongalo et al., 2020).

The genus *Ziziphus* within the Rhamnaceae family comprises over 58 recognized species of thorny shrubs and small trees, predominantly found in arid and semi-arid regions. These species are traditionally celebrated for their health benefits, nutritional values, and therapeutic properties, as documented across various cultures, particularly in India, Pakistan, China, and the Middle East (Golla, 2018). *Ziziphus* species serve as a rich source of bioactive compounds. Phytochemical analyses have identified approximately 431 chemical constituents to date, which include alkaloids (notably cyclopeptide alkaloids), flavonoids, terpenoids, saponins, and additional minor compounds such as cholinergic acids, aromatic and polyaromatic compounds, steroids, cerebrosides, and nucleosides (El Maaiden et al., 2020).

3.5.1 *Ziziphus nummularia* (Burm.f.) Wight & Arn.

Z. nummularia is a small, thorny, branched shrub native to India, Pakistan, and Iran, predominantly found in arid and dry regions (Figure 3.60). This species is extensively utilized in traditional folk medicine. Its fruit serves as a food source, known for its cooling properties and ability to alleviate biliousness. The powdered form of the ripened fruit has been reported to relieve constipation. The

FIGURE 3.60 *Ziziphus nummularia.*

leaves are employed in treating various conditions, including scabies, skin disorders, conjunctivitis, diarrhea, gastrointestinal spasms, and helminthiasis. The roots are traditionally used for dysentery, while the stem bark is applied to mitigate joint pain, sore throat, and bleeding gums (Upadhyay et al., 2011). Cyclopeptide alkaloids are natural macrocyclic compounds known for their intriguing chemical and biological properties, prominently found within the Rhamnaceae family and specifically the *Ziziphus* genus. The compounds have been implicated in central nervous system functions, exhibiting sedative, analgesic, and anti-nociceptive effects, along with antimicrobial properties and potential antidiabetic activity. This has garnered significant interest from chemists and biologists aiming to elucidate the structure-activity relationships of these compounds, positioning them as a promising source of therapeutic agents (Mesmar et al., 2022; Tuenter et al., 2017). The plant is rich in a variety of bioactive compounds, including alkaloids, cyclopeptide alkaloids, flavonoids, saponins, fatty acids, and triterpenoids. Its high tolerance to environmental stress enhances its ease of cultivation, making it increasingly valuable for farmers, particularly in situations of crop failure (Khan et al., 2020b).

Z. nummularia is a valuable wild plant adapted to arid climates, recognized for its ripe fruits as food, leaves as livestock forage, and utility in living fences, furniture, and building materials. Furthermore, it serves medicinal purposes and provides fuelwood. The leaves of *Z. nummularia* shed in winter, followed by the onset of fruiting. These leaves are harvested, sun-dried, and processed for future use, with intentional collection occurring twice a year for local marketing (Azhar & Zubair, 2019). A decoction made from the leaves of *Z. nummularia* is employed in the treatment of coughs, colds, and typhoid fever. Moreover, a paste of the leaves is applied for the healing of cuts and skin disorders (Padalia & Chanda, 2017).

The anti-inflammatory properties of *Z. nummularia* are evidenced by its capacity to enhance wound healing, decrease inflammatory markers in various in vivo models of inflammation, and inhibit the production of nitric oxide and TNF-α from activated macrophages in vitro (Fardoun et al., 2017). Desert rural communities utilize the roots, leaves, and seeds of the plant to treat various ailments, including allergies, scabies, eczema, and pyorrhea (Sonia & Singh, 2019). Due to their abundance of bioactive metabolites, plants in the *Ziziphus* genus have been recognized for their therapeutic potential in treating a range of conditions, including fever, diarrhea, skin infections, conjunctivitis, helminthiasis, and gastrointestinal disorders. Moreover, they have demonstrated antioxidant, anti-inflammatory, antimicrobial, and antinociceptive activities (Abdallah et al., 2024).

3.5.2 *Ziziphus jujuba* Mill.

Z. jujuba, commonly known as jujube, is a desert-adapted medicinal food source valued for its rich nutrient profile and therapeutic properties (Figure 3.61). This resilient species thrives in arid climates and is known for its fruits, which are high in vitamins, minerals, and antioxidants, contributing to overall health and wellness. Traditionally utilized in various cultures for their health benefits, jujube fruits are recognized for their potential in alleviating ailments such as insomnia, digestive issues, and respiratory disorders. Jujube, a member of the genus *Ziziphus* within the Rhamnaceae family, is predominantly cultivated in subtropical and tropical regions, especially in Australia, southern and eastern Asia, and Europe. This species has been cultivated for over 4,000 years in China, where it is primarily found in the northwest, particularly in the Yellow River Valley, including Ningxia, Shaanxi, and Shanxi provinces, as well as in the eastern regions (Gao et al., 2013). The polysaccharides isolated from *Z. jujuba* using various extraction and purification methods are structurally diverse biomacromolecules exhibiting a range of physicochemical properties and biological activities. These polysaccharides demonstrate significant immunomodulatory, antioxidant, antitumor, hepatoprotective, and hypoglycemic effects, along with gastrointestinal protective properties (Ji et al., 2017; Xie et al., 2016). Many cultures have utilized *Z. jujuba* for medicinal purposes. In eastern, southeastern, and central Iran, where the plant is referred to as "annab", it is used in traditional medicine to address digestive disorders and gastric ulcers, following prescriptions from Avicenna. However, it is employed as an antitussive, laxative, and hypotensive agent (Villanueva & Villanueva, 2017).

FIGURE 3.61 *Ziziphus jujube.*

There are five forms of *Z. jujuba* (ZJ) available: *Z. jujuba* fruit (ZJF), *Z. jujuba* leaves (ZJL), *Z. jujuba* core (ZJC), *Z. jujuba* bark (ZJB), and *Z. jujuba* roots (ZJR). Among these, ZJF is the most commonly utilized in traditional Chinese medicine (TCM) prescriptions (Ruan et al., 2024). ZJB possesses a bitter and acerbic flavor with warming properties, making it effective for conditions related to the lung and large intestine meridians. It is utilized for astringing the intestines and alleviating diarrhea, suppressing coughs, and stopping bleeding. ZJB is noted to be beneficial for diarrhea, dysentery, cough, and abnormal uterine bleeding. For oral administration, 6–9 g of the ground powder can be decocted in water, or 1.5–3 g of the powder can be taken with water. In cases of bleeding from traumatic injuries or burns, appropriate amounts may be used externally by decocting in water for douching or grinding into powder for direct application (Liu et al., 2021). ZJF and its extracts are promising natural sources of antioxidants in the food industry; however, the fundamental metabolic functions of ROS warrant further investigation. The potential use of ZJF as a dietary supplement for the prevention of neurodegenerative diseases associated with neurotrophin deficiency is also noteworthy. Recognized globally, *Z. jujuba* and its fruit (ZJF) are included in the Chinese pharmacopoeia, highlighting their significance in both the food sector and health care (Siriamornpun et al., 2015).

3.6 BIOCHEMICAL THERAPEUTIC USES OF DESERT WEs OF ZYGOPHYLLACEAE

Desert plants of the Zygophyllaceae family, such as *Fagonia cretica* and *Tribulus terrestris*, have shown promising biochemical properties that can be harnessed for therapeutic applications, including anti-inflammatory, antioxidant, and antimicrobial effects. These plants are not only valuable for their medicinal benefits but also play a crucial role in enhancing food security in arid regions.

Through the facilitation of cultivation and sustainable use of Zygophyllaceae species, communities can diversify their food sources and utilize the plants as functional foods, rich in nutrients and bioactive compounds. This approach not only supports local health and nutrition but also contributes to the resilience of desert ecosystems, ensuring that vulnerable populations can thrive even in challenging environments.

3.6.1 *Fagonia cretica* Linn.

F. cretica, commonly known as the desert thorn, is a resilient plant native to arid regions, particularly in Africa and the Middle East (Figure 3.62). Renowned for its medicinal properties, this hardy species belongs to the Zygophyllaceae family and thrives in harsh desert environments. Traditionally, *F. cretica* has been used in folk medicine for its anti-inflammatory, antimicrobial, and antioxidant effects, making it a valuable resource for addressing various health issues. The leaves and stems of the plant are often utilized in herbal preparations to treat ailments such as fever, digestive disorders, and skin infections. In addition to its therapeutic benefits, *F. cretica* also holds promise as a functional food source, rich in essential nutrients and bioactive compounds (Ahmed et al., 2013). Beier et al. (2004) classified *F. cretica* as an ancestral species, serving as a sister to all *Fagonia* species except *Fagonia scoparia* and *Fagonia zilloides*. The genus *Fagonia* comprises 34 species that are primarily found in warm and arid regions of Eurasia, Africa, and the Americas (Spampinato et al., 2018).

F. cretica is a plant of high medicinal value that has garnered significant interest among pharmacists due to its demonstrated therapeutic potential in preliminary pharmacological studies

FIGURE 3.62 *Fagonia cretica.*

(Kiani et al., 2022). This green, erect, spiny shrub typically reaches heights of 1–3 feet and is predominantly found in Algeria, Egypt, Tunisia, Cyprus, Morocco, Saudi Arabia, and on dry calcareous rocks across western India and Pakistan. The plant has a bitter and sour taste, with notable medicinal properties that address various hepatic, hematological, neurological, and inflammatory conditions (Faisal et al., 2022). *F. cretica* is a widely utilized ethnomedicinal plant known for its diuretic, laxative, carminative, emetic, and abortifacient properties. Moreover, it has demonstrated anti-diabetic, antipyretic, antioxidant, antimicrobial, and anti-hemorrhagic effects. The diverse activities are largely attributed to its abundance of secondary metabolites, including flavonoids, saponins, alkaloids, terpenoids, coumarins, tannins, and sterols, as indicated by preliminary phytochemical analysis (Kamran et al., 2023).

One of the most well-known remedies associated with *F. cretica* is the aqueous extract of its aerial parts, which is reported to be particularly effective for early-stage cancer therapy. The entire plant is dried, chopped, and ground into a powder, which is then extracted using a range of polar to non-polar solvents. This can be done through methods such as soaking, shaking, dispersing, or decoction. Recent quantitative assessments of the crude phytochemicals in the dried plant material have revealed significant levels of alkaloids, flavonoids, glycosides, phenolic compounds, pectin, and total protein content, along with three key vitamins: riboflavin (B2), niacin (B5), and ascorbic acid (C) (Hussain et al., 2011; Qureshi et al., 2016). Methanolic extracts of *F. cretica* have demonstrated notable antimicrobial activity, along with significant free radical scavenging capabilities against reactive oxygen and nitrogen species, and exhibit anti-diabetic effects (Rajani et al., 2022).

In traditional medicine, *F. cretica* is recognized for its anti-bilious, antiseptic, and blood-purifying properties. Internally, it is typically administered as a decoction and used as a gargle for conditions such as stomatitis and other oral diseases. Externally, a paste made from the plant is applied to treat boils, wounds, and scrofulous glands. In the Indo-Pak subcontinent, this plant is employed in the treatment of various ailments, including typhoid, scabies, fever, asthma, urinary issues, bronchitis, tumors, liver disorders, piles, and digestive problems (Khan et al., 2023). The plant serves as a bitter tonic, diuretic, astringent, and prophylactic agent against smallpox. It is also employed in the treatment of dysentery, asthma, fever, thirst, vomiting, urinary disorders, liver issues, dyslipidemia, typhoid, toothache, gastrointestinal disturbances, and various skin conditions (Patel & Kumar, 2020).

3.6.2 *T. terrestris* L.

T. terrestris, commonly known as puncture vine, is a resilient botanical species that thrives in arid and semi-arid environments, making it a valuable resource in desert ecosystems (Figure 3.63). This plant has garnered attention for its nutritive potential, offering a range of essential nutrients and bioactive compounds that can support both human and animal health. Rich in vitamins, minerals, and phytochemicals, *T. terrestris* has been traditionally used in various cultures for its medicinal properties and as a food source. Its adaptability to harsh conditions emphasizes its significance as a sustainable nutritional option in regions where conventional agricultural practices may be challenging (Dinchev et al., 2008). *T. terrestris* has gained significant attention in the global nutritional supplement market. Historically, this plant has been utilized in traditional medicine across Greece, China, and India for addressing issues such as infertility, impotence, erectile dysfunction, and low libido. Since the early 1980s, its extracts have become popular in unconventional medicine in Western countries, often marketed as a testosterone booster, libido enhancer, and adaptogen for healthy, physically active men (Pokrywka et al., 2014). Phytochemical analysis of the whole plant extract resulted in the identification of seven new steroidal saponins, including six furostanol saponins and one spirostanol saponin, as well as four previously known steroidal saponins (Figueiredo et al., 2023).

T. terrestris plant has traditionally been employed for its cardiotonic, appetite-stimulating, aphrodisiac, anti-urolithiasis, diuretic, emollient, anti-helminthic, digestive, and antibacterial

FIGURE 3.63 *Tribulus terrestris.*

properties. Due to its potassium-sparing, cardioprotective, and anti-hyperlipidemic effects, *T. terrestris* may serve as a potential herbal therapy for effective blood pressure management. Moreover, dietary supplements containing *T. terrestris* extracts are said to improve muscle tone, provide biostimulating effects, and enhance spermatogenesis (Gunarathne et al., 2023). *T. terrestris* contains a significant protein content of 21.33%, making it a valuable protein source, along with a rich supply of essential minerals. It effectively provides important minerals such as potassium, calcium, and copper (Saeed et al., 2024). The green leaves of *T. terrestris* (per 100 g) consist of 79.09% moisture, 7.22% protein, 1.55% calcium, 0.08% phosphorus, 9.22 mg of iron, and 41.5 mg of vitamin C. Furthermore, the powdered root extract contains resins, alkaloids, nitrates, and oils (Adaikan et al., 2001; Semerdjieva & Zheljazkov, 2019). Globally, numerous pharmaceutical preparations and herbal supplements contain extracts standardized for steroidal saponins. These products are primarily indicated for libido disorders in both males and females, as well as for erectile dysfunction and abnormal sperm motility (Singh et al., 2023a; Ştefănescu et al., 2020). In China, the fruits of *T. terrestris* are regarded as beneficial for preventing kidney issues, alleviating coughs, and improving eyesight. In Ayurveda, the fruits are used to address infertility, while the roots are recognized for their cardiotonic properties (Abbas et al., 2022). Furthermore, it is a nutritional supplement that is the subject of considerable debate concerning its physiological effects and overall impact on the body (Ghanbari et al., 2021).

The calcium, iron, and zinc content in the raw materials of *T. terrestris*, while high, is not suitable for significantly supplementing intake. This is because plant sources rich in bi- or tri-valent ions often have low bioavailability due to the presence of phytic acid, polyphenols, and tannins, which severely restrict mineral absorption. Despite other beneficial effects, phytic acid acts as an antinutrient in relation to mineral uptake (Tkachenko et al., 2020). *T. terrestris* plant, commonly known as

small caltrops, land caltrops, or puncture vine, is a dicotyledonous species that thrives in harsh and dry climates. It grows abundantly across Asia, Africa, Europe, and Australia, particularly in sandy soils and arid conditions. Historically, *T. terrestris* has been utilized in the traditional medicinal practices of various cultures. Nutritionally, it is significant due to its unique combinations, being rich in dietary fibers and essential minerals that are vital for human health. It helps alleviate gastrointestinal issues and positively impacts digestion and nutrient absorption. Incorporating *T. terrestris* into products enhances water absorption capacity and demonstrates remarkable foaming and emulsification abilities, although it has minimal effects on oil absorption and bulk density (Khalid et al., 2023). Preparations containing *T. terrestris* extract are currently available as dietary supplements in the United States and Europe, where they are marketed for their purported stimulating effects on athletic performance, muscle tone, and overall rejuvenation (Zhang et al., 2023).

The biological properties of this plant species include antimicrobial, antibacterial, antioxidant, cyclooxygenase inhibition, free radical scavenging, and inhibition of fat peroxidation, as well as the modulation of inflammatory factors. It is utilized in traditional medicine to address a range of conditions, including liver diseases, kidney stones, hypertension, diabetes, cardiovascular diseases, and gastrointestinal disorders (Shams et al., 2020). Diosgenin, a naturally occurring compound in *T. terrestris*, is recognized as an isoprostane derivative, a steroidal sapogenin, and a precursor for steroidal medications. Due to its beneficial effects on chronic conditions such as high cholesterol, stroke, diabetes, obesity, Alzheimer's disease, inflammation, leukemia, climacteric syndrome, depression, thrombosis, cancer, and other metabolic disorders, it is increasing in popularity (Arya et al., 2023; Zahedi et al., 2024).

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4 Economic Botany of the Desert WEs

Source of Food and Nutrition

4.1 WES: COMBATING FOOD AND HEALTH SECURITY

In arid desert landscapes, where traditional agricultural practices often face significant challenges due to water scarcity and harsh climatic conditions, wild edibles (WEs) emerge as a vital resource for enhancing food and health security. The naturally occurring plants, which have adapted to survive in extreme environments, offer diverse nutritional benefits and can serve as a sustainable food source for local communities. The economic potential of WEs lies not only in their role as a supplemental food source but also in their capacity to stimulate local economies through foraging, processing, and selling activities. The incorporation of WEs into local diets, economies, and communities can reduce their reliance on imported food supplies, which are often expensive and less nutritious. Moreover, the promotion of WEs supports biodiversity conservation and sustainable land management practices, which are essential for maintaining the ecological balance in fragile desert ecosystems. This multifaceted approach addresses critical issues of food and health security, empowering communities to leverage their natural resources while fostering resilience against the socio-economic impacts of climate change and food insecurity. With extensive research, education, and policy support, the potential of WEs can be fully realized, transforming them into a cornerstone of sustainable development in desert regions.

WEs are essential elements of traditional and indigenous food systems, recognized for their role in enhancing food security while remaining vulnerable to global changes. These food systems rely heavily on healthy ecosystems, which face significant sustainability challenges compared to other human activities. Global environmental changes, including climate change and land-use alterations, further exacerbate these challenges (Downs et al., 2020). Traditional and indigenous food systems are often defined as place-based systems where communities gather both wild and cultivated foods from their local environments. From a human health perspective, the consumption of wild foods contributes to food security and promotes dietary diversity through the inclusion of nutrient-dense options. This, in turn, helps combat micronutrient deficiencies and chronic diseases, thanks to the rich nutrient and phytochemical profiles of WEs (Ahmed et al., 2022; Vinceti et al., 2012). Ensuring food security for humanity has become increasingly challenging in the 21st century, a time marked by unprecedented technological advancements across various domains. While the environmental costs associated with these technologies can be significant, there is potential to counteract food insecurity and food safety issues by harnessing appropriate technologies designed to address these challenges effectively (John & Babu, 2021).

The semi-arid and arid agro-climatic zones of the subcontinent are home to a variety of plants, many of which grow wild and remain underutilized in desert landscapes, producing edible fruits. These plants thrive in extreme temperatures and on marginal lands under water-scarce conditions, positioning them as sustainable food sources for the future. Their benefits to ecosystems and communities are numerous: (1) They can enhance agricultural productivity for other crops,

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such as cereals, within agroforestry systems; (2) they serve as balanced functional foods, offering high-quality protein along with essential macro- and micronutrients to address protein-calorie malnutrition; and (3) they provide sources of antioxidants, nutraceuticals, and bioactive compounds to help combat the growing prevalence of non-communicable diseases, including obesity, diabetes, and cardiovascular disorders. A population-based survey was conducted to assess the incidence of food shortages and the coping mechanisms employed, as well as to evaluate the knowledge, attitudes, and practices related to the consumption, conservation, and management of wild and semi-wild edible species. Long-standing cultural practices surrounding the conservation, management, and utilization of WEs were also examined. Planning for the promotion, sustainable use, and conservation of WEs must take into account the knowledge and practices of local communities, as these play a crucial role in initiatives aimed at food security and sovereignty (Addis et al., 2013).

Deserts represent unique ecosystems characterized by some of the most severe climatic conditions for plant growth. To endure extreme temperatures and limited water availability, desert flora develop and enhance their metabolic pathways with a wide array of natural compounds. These adaptations equip them to withstand both abiotic and biotic stressors effectively (Asati et al., 2021). The metabolites contribute both nutritional and nutraceutical value to the foods derived from these plants. In the arid and semi-arid regions of the Indian subcontinent, several edible plants featured in this study include nitrogen-fixing tree legumes such as *Prosopis cineraria* and *Acacia senegal*, shrub legumes like *Cyamopsis tetragonoloba* (cluster bean), and non-legumes such as millets, *Capparis decidua*, *Ziziphus mauritiana* (Indian jujube), *Cordia dichotoma*, *Leptadenia pyrotechnica*, and *Calligonum polygonoides* (Joshi et al., 2023). Many desert plants grow wild, and their biochemical and nutritional characteristics are often influenced by multiple genes and shaped by environmental factors. Therefore, from both agricultural and industrial viewpoints, it is crucial to select and cultivate the appropriate genotypes for specific food or medicinal purposes (Ali et al., 2014).

Underutilized wild plants have been vital sources of nutrition and medicine since ancient times, contributing to food security, enhancing dietary diversity, and preventing malnutrition. Currently, the global average consumption of healthy foods falls significantly below recommended dietary intakes, while the intake of highly processed, energy-dense, and nutrient-poor foods continues to rise. This shift in food choices is driven by lifestyle standardization, advancements in food production and processing technologies, and limited time for culinary activities. Furthermore, these plants represent crucial biological assets for low-income populations and play a significant role in improving the well-being of tribal communities. It is essential to explore the untapped potential of these underutilized plants to address food security, unemployment, and environmental degradation. The management of crops into local food systems can help alleviate malnutrition, particularly in rural communities where farming serves as the primary source of food and income (Nirmala et al., 2022).

4.1.1 Nutritional Benefits of WEs in Arid Regions

Wild food plants have historically played a crucial role in traditional food systems, especially among rural populations worldwide. However, in many areas, reliance on these plants has significantly decreased due to sociocultural shifts and the impacts of global climate change (Waheed et al., 2023). Throughout history, wild food plants have been integral to diets and traditional food practices, providing essential nutrients and bioactive compounds. Parts of wild food plants such as fruits, flowers, roots, and tubers are rich in fiber, protein, fats, and carbohydrates, offering the necessary nutrients for a balanced daily diet, particularly in arid desert regions where food security can be challenging (Majeed et al., 2021). The scarcity, high costs, and inconsistent availability of

nutritious food in developing countries have driven the search for affordable and alternative sources of healthy sustenance. WEs emerge as a vital alternative, playing a crucial role in bolstering the global food supply across various regions. The WE plants significantly contribute to meeting nutritional needs and enhancing the health of impoverished communities, particularly in rural areas of arid desert regions (Assefa & Abebe, 2011). The rural populations rely on WE plants as a survival strategy during periods of drought, famine, and other crises. Rich in essential nutrients such as protein, vitamin B2, and vitamin C, these plants serve as viable substitutes for conventional plant-based diets. Moreover, existing research indicates that some WEs possess medicinal properties. Despite their importance for food security, WE plants are often undervalued and seen as food only for the economically disadvantaged (Duguma, 2020).

In recent decades, the nutritional, ecological, socio-economic, and livelihood benefits of WEs have gained recognition due to increasing modernization and globalization (Bharucha & Pretty, 2010). However, they remain underrated, neglected, and underutilized in desert regions. Overlooking the value of wild foods adversely affects the ecosystem provisioning services and jeopardizes the preservation of traditional knowledge systems linked to indigenous food supply chains, which are essential to understand in the context of changing lifestyles and environmental conditions (Mishra et al., 2021). Local populations, particularly tribal communities, actively manage local biodiversity and utilize their traditional knowledge to fulfill their socio-cultural and economic needs, thereby ensuring food and nutritional security even in arid desert zones (Singh et al., 2023). Various local plant species, including fruit trees, shrubs, and annual creepers, thrive naturally in these environments, and many have been recognized for their ethnomedicinal properties. The ecosystem fragility, exacerbated by climatic stress and poverty, has driven local communities to deepen their engagement with their surroundings to sustain their livelihoods and secure adequate food and nutrition (Pasqualone et al., 2020).

4.1.2 Sustainable Harvesting Practices for Desert Foraging

Planning and managing sustainable agriculture in drylands present significant challenges but also offer immense potential. The primary challenge lies in limited resources, particularly low water availability and poor soil quality. However, the opportunity is substantial, as over 40% of the Earth land cover consists of drylands (Shelef et al., 2016). Domestication typically involves cultivating wild plants for human use, primarily for food sources such as grains and legumes. This process includes developing plants not only for food and medicinal purposes but also for oilseed production, which has diverse applications and can serve as a green belt to mitigate environmental risks and combat desertification (Das et al., 2015; Schimel, 2010). Deserts offer the potential for discovering new medicinal sources derived from their uniquely adapted plants and animals, which thrive in harsh and unpredictable environments. However, these deserts face threats from unsustainable human activities, excessive water extraction, and climate phenomena, all of which contribute to the encroachment of desert areas into previously vegetated regions (Mukhopadhyay, 2008).

Wild-harvested plant foods encompass a variety of categories, including roots and other underground parts, shoots and leafy greens, berries and fleshy fruits, grains, nuts, and seeds, as well as mushrooms, lichens, algae, and other species. Utilizing these resources necessitates specialized cultural knowledge related to harvesting, preparation, cooking, and other processing methods (Turner et al., 2011). Climate change is significantly reshaping agriculture and harming crops, food security, and human health, particularly in desert regions. To effectively redesign food systems that can withstand climatic disruptions, it is essential to prioritize agroecological functions, human health, and community well-being. This involves selecting a more diverse array of arid-adapted food crops to mitigate vulnerabilities in food systems related to climate change, climate-induced illnesses, and economic inequalities in arid landscapes (Nabhan et al., 2020). Arid rangelands are among the most vital ecosystems, offering a wide range of services and serving as habitats for pastoral and agro-pastoral communities. They encompass diverse habitats and ecological communities, making them

economically significant due to their abundant edible plants, forage species, and medicinal and economically valuable plants. Any disturbances in the plant biodiversity of desert rangelands have more pronounced and profound effects compared to other ecosystems, emphasizing the importance of sustainable harvesting and management practices (Gamoun & Louhaichi, 2021).

Arid lands are characterized by unique biological and cultural diversity, and the loss of biodiversity in these regions can disproportionately affect their ecosystems due to low redundancy and a heightened risk of trophic cascades. These areas are home to many endemic species, including wild relatives of important edible crops. However, extensive agriculture, unsustainable resource use, and global climate change are causing irreparable damage to arid lands, leading to significant consequences for species, groundwater resources, ecosystem productivity, and the communities that rely on these systems (Zhang et al., 2023). References to arid ecosystems in UN sustainability agendas and the Sustainable Development Goals (SDGs) often focus on ecosystem manipulation to combat desertification, conflating arid lands with degraded systems and failing to differentiate between these fragile natural environments and the degradation seen in other ecosystems (López-Carr et al., 2023). Arid ecosystems are defined by limited availability and mobility of soil nutrients, along with slow geochemical cycles. The management of native vegetation for purposes such as fuel, livestock grazing, and other agricultural practices (including burning and cutting) can pose a threat to semi-natural communities by disrupting nutrient cycles and affecting soil fertility (Tariq et al., 2022).

4.1.3 Cultural Significance and Traditional Knowledge of Wild Foods

Wild foods, particularly those sourced from desert ecosystems, hold profound cultural significance and are imbued with traditional knowledge that has been passed down through generations. These foods not only sustain local communities but also reflect the intricate relationship between people and their environment. In arid landscapes, where agricultural practices may be limited, indigenous and local populations have developed an intimate understanding of native flora and fauna, utilizing them for nourishment, medicine, and spiritual practices. Traditional ecological knowledge (TEK) plays a crucial role in the sustainable harvesting and preparation of these WEs, often informing practices that ensure the conservation of biodiversity (Hodgson, 2015). Furthermore, desert WEs, such as prickly pear, mesquite pods, and various desert greens, are rich in nutrients and offer unique flavors that contribute to culinary diversity. The interest in foraging and sustainable food practices is growing, and there is an increasing recognition of the value of these traditional foods, not only as sources of sustenance but also as cultural symbols that embody identity, resilience, and ecological wisdom. This intersection of culture, ecology, and gastronomy highlights the importance of preserving traditional knowledge systems that support the continued appreciation and use of desert WEs (Singh & Bedi, 2018). Documenting traditional knowledge of WEs and medicinal plants through ethnobotanical surveys is essential for safeguarding this invaluable information from being lost with the passing of its elderly custodians. Such efforts not only help preserve this knowledge but also promote the value of both medicinal and aromatic flora used in food (Mechaala et al., 2022; Nawash et al., 2013).

Considering the diverse strategies employed by societies in drylands to adapt their lifestyles and activities to environmental constraints, local ecological knowledge (LEK) systems may be specifically tailored to address these challenges. This adaptation can significantly influence the resilience of LEK in relation to the use of edible food sources, allowing communities to effectively navigate and thrive in harsh conditions (Berkes et al., 2000; Blanco & Carrière, 2016). WE plants play a vital role in supporting the global food supply, benefiting approximately 1 billion people daily. They serve as essential resources for rural communities, particularly during periods of drought, famine, and other crises. WEs encompass all non-domesticated plant species utilized by humans, reflecting the co-evolutionary relationships between people and their environments (Tebkew et al., 2018). WEs can enhance dietary diversity, provide sustenance during food shortages, supplement household income, and offer genetic material for research. Moreover, they hold significant cultural

and spiritual value for rural communities, contributing to their overall resilience and well-being (Assefa & Abebe, 2011). While all societies are embedded within their environments, their choices and actions are shaped by culturally constructed values, beliefs, and priorities. In many developing regions, communities heavily depend on local environmental resources, particularly WE plants, for their daily sustenance and healthcare. The traditional knowledge of these resources, transmitted across generations, serves as a reservoir of resilience, playing a critical role in group survival during challenging times. The differences in knowledge and practices between two cultural groups inhabiting the same ecosystem are particularly noteworthy, as they reveal how cultural perspectives can not only influence human perceptions of the environment but also direct interactions with the resources inherent in that ecosystem (Quave & Pieroni, 2015).

WEs continue to hold significant importance in both the food systems and cultural practices of the study area, with a rich repository of folk knowledge associated with them in the desert region. However, this knowledge is diminishing among younger generations. The documented species authorization re-evaluation in local initiatives focuses on promoting endogenous food security strategies, as well as preserving cultural heritage and supporting small-scale food market networks (Ahmad & Pieroni, 2016). WEs are crucial for complementing staple diets in arid desert regions, thanks to their exceptional nutritional profile. They serve as rich sources of minerals, fiber, vitamins, and fatty acids, enhancing both the flavor and color of the diet (Tardío et al., 2006). One of the most promising avenues in contemporary ethnobiological research is the cross-cultural comparison of wild food plant usage among neighboring ethnic or religious groups, as well as within diasporas (Pieroni et al., 2017). Data from these studies can enhance discussions on how intricate cultural and social factors influence the selection and preference for WE plants in local cuisines, as well as the prevalence of specific food processing methods, provided that the available edible plant resources are consistent (Bellia & Pieroni, 2015). It is essential to organize the documented information on WEs in user-friendly formats for accessibility by local desert communities. Moreover, developing propagation protocols for highly valued WE species will support a deliberate domestication initiative, thereby lessening reliance on wild populations. Furthermore, it is important to clarify the nutritional contributions of these plants to human diets and investigate their potential trade-offs in the context of desert reserve management (Ojelel et al., 2019).

4.1.4 Wild Edibles as a Strategy for Food Security and Ecological Resilience

The importance of WEs in enhancing food and nutritional security for marginalized communities is well-recognized. However, there is insufficient information regarding the extraction, consumption, and trade of WEs in desert regions, particularly in Kashmir, where their actual contribution remains unquantified. This study aims to investigate the diversity, extraction methods, consumption habits, and trade dynamics of WEs within desert landscapes. Wild food plants, often neglected in national reports and conservation initiatives, have been essential for food and nutrition security for centuries. Recently, various countries have highlighted the regular consumption of WEs, especially among rural and indigenous communities in desert areas (Peerzada et al., 2024). These plants are crucial for livelihood resilience and provide vital micronutrients to populations facing food shortages or emergencies. However, threats such as land use changes, climate change, overexploitation, and urbanization are diminishing the availability of these resources in the wild and contributing to the erosion of traditional knowledge regarding their use (Borelli et al., 2020). WEs could play a pivotal role in empowering local market actors and minimizing the gap between consumers and producers, thereby reducing dependence on globalized value chains (Rowland et al., 2017). The COVID-19 crisis has exposed the fragility of global food systems to disruptions and shocks related to disease. Food shortages impact specialized, high-value horticultural crops. Individuals are increasingly turning to traditional vegetables and WEs as sustainable sources of food, vitamins, and nutrients. Moreover, WE plants serve as valuable resources for herbal ingredients, traditional medicine formulations, and emerging biopharmaceuticals (Torero, 2020; Vandebroek et al., 2020).

The role of WE foods in addressing food shortages is critical. However, current strategies to tackle food insecurity have primarily concentrated on reducing vulnerability by increasing the productivity of domesticated crops. In contrast, less emphasis has been placed on approaches that enhance resilience through the use of wild food sources. WEs play a significant role in helping households in arid desert regions withstand food shortages, particularly among indigenous communities compared to non-indigenous groups. Therefore, it is essential to adopt resilience-building policies that incorporate wild foods, along with conducting urgent research to explore their current status and future potential (Guyu & Muluneh, 2015). Climate change is exacerbating agricultural crop failures and reducing the availability of wild food harvests for indigenous desert communities. This crisis in food production hampers ongoing efforts by these communities to achieve greater food security, leading them to reevaluate the significance of traditional indigenous food systems (Nabhan et al., 2022). In the context of a changing climate, the sustainable productivity of desert rangelands (arid and semi-arid regions) relies on cultivating drought-resistant crops and developing sustainable cropping systems. Areas such as Thal, Thar, Cholistan, and Kharan in Pakistan are experiencing increased duration, intensity, and frequency of drought, leading to significant water, food, and feed shortages that contribute to malnutrition, hunger, and even mortality (Diniz et al., 2017). The food security of the rapidly growing population in these regions is jeopardized by the scarcity of forages, resulting in low productivity of ruminants. To address this issue, it is essential to cultivate crops with moderate to high carrying capacity, quick utilization potential, and the ability to recover swiftly after heavy grazing (Neffar et al., 2013). However, these crops should exhibit drought tolerance, rapid establishment, low production costs, high resilience to soil toxicities and unpredictable weather conditions, and should be safe for ruminant health (Iqbal et al., 2020).

It is estimated that up to 45% of the world cultivated plants originated in drylands. Agriculture, agroforestry, and agroecology in desert regions have long relied on this genetic diversity. The ongoing UN Decade on Ecosystem Restoration (2021–2030) presents a unique opportunity to reshape desert landscapes and create more biodiverse and nutritious food systems. However, many large-scale restoration initiatives remain largely disconnected from the socioeconomic challenges faced by dryland communities, particularly concerning food security and acute malnutrition (Sacande & Muir, 2023). The FAO experience indicates that the timing and choice of plant species can significantly enhance biodiversity, reverse land degradation, and positively impact nutritional outcomes. Future interventions in desert regions must foster collaborative efforts between nutritionists and natural resource managers to benefit both human health and planetary well-being (James et al., 2013). The desert ecosystem faces a range of environmental challenges, including low rainfall, drought, high soil salinity, extreme temperatures, intense sunlight, low moisture retention, and infertile soils, all of which collectively affect plant growth and development (Pinela et al., 2017). Recognizing the relative importance and preferences of various species is essential for the sustainable management of local forage resources. This understanding can aid animal husbandry technicians in optimizing the selection of beneficial fodder species, thereby enhancing the efficiency of livestock systems within the desert ecosystem (Shahid et al., 2023).

4.1.5 Policy Recommendations for Promoting Wild Edibles in Desert Economies

The desert economic resources face increasing challenges related to food security, and the promotion of WEs offers a sustainable solution to enhance local nutrition and economic resilience. WE plants, often overlooked, can provide vital sources of vitamins, minerals, and other nutrients that are scarce in conventional agricultural produce within arid regions. The plants are well-adapted to harsh climates, requiring minimal water and care, making them ideal for cultivation in desert environments. Integrating WEs into local diets can not only mitigate the reliance on imported food but also stimulate local economies by creating opportunities for foraging, cultivation, and trade. Moreover, traditional knowledge surrounding WEs can be harnessed and preserved, fostering cultural heritage and community engagement. By implementing targeted policy

recommendations that promote the identification, sustainable harvesting, and commercialization of WEs, governments and organizations can improve food security and bolster the livelihoods of desert communities. Such initiatives could involve educational programs, the establishment of foraging cooperatives, and support for local markets, ensuring that WEs contribute to a diversified and resilient food system that respects both ecological integrity and cultural traditions.

References to arid ecosystems within UN sustainability agendas and the SDGs often focus primarily on ecosystem manipulation to combat desertification, mistakenly equating arid lands with degraded environments without acknowledging the unique characteristics of these fragile systems (Imeson, 2011). Alarmingly, deserts and rocky ecosystems host the second-highest proportion of critically endangered plant species across all ecosystems in global analyses. Unsustainable practices, such as the overexploitation of biological resources, have resulted in significant declines in native populations, with some species facing extinction (Hobohm et al., 2021). For instance, the population of *Haloxylon ammodendron*, a dominant shrub in many Central Asian desert ecosystems, has plummeted by 60% in the Junggar Desert due to drought conditions and unsustainable harvesting for firewood and livestock (Ling et al., 1998). This pressing situation necessitates a collaborative effort among researchers, practitioners, policymakers, and local communities to adopt a socio-ecological framework for achieving sustainable development in arid regions. Establishing an arid lands biodiversity data initiative is essential for mapping species distributions, monitoring population trends, and facilitating evidence-based management and policy strategies (Zhang et al., 2023). Desertification currently impacts 1.5 billion people worldwide, resulting in an estimated $42 billion in lost agricultural earnings. Various large-scale reforestation initiatives have been launched to recover land affected by desertification, primarily through the planting of millions of trees (Kirschner et al., 2021). Notable examples include the 8,000 km Great Green Wall across Africa and a similar initiative in the Gobi Desert. In this context, desert plants are crucial for the success of reforestation efforts. These desert survivors have evolved unique morphological and physiological traits that enable them to thrive in infertile soils characterized by high salinity and low nutrient availability, making them ideal candidates for restoring desert landscapes. Furthermore, the diversity of desert plant species ranging from grasses to shrubs and trees offers valuable options for land restoration and landscaping, providing alternatives to traditional species that require regular irrigation (Blilou & Hirt, 2023).

Revegetating native desert vegetation poses significant challenges due to the multitude of ecological factors that influence the process. It demands careful planning and a systematic approach that accounts for these various influences (Han et al., 2014). Many revegetation initiatives have encountered failures due to the arbitrary dispersal of seeds and seedlings in locations that are unsuitable for growth. Successful revegetation of native desert plants is contingent upon several factors, including topography, soil type, and climatic conditions such as temperature, humidity, and precipitation (Asadalla et al., 2021; Winkler & Brooks, 2020). Deserts are increasingly identified as prime locations for solar energy development; however, the effects of this expansion on desert plant communities remain largely unexplored (Grodsky & Hernandez, 2020). Desert plants serve as vital ecological, economic, and cultural resources, particularly for indigenous peoples who have relied on them for generations as food sources in WE food species, as shown in Figure 4.1.

Countries and regions participating in the Belt and Road Initiative have historically faced significant challenges from desertification, land degradation, and drought, making them some of the most severely affected areas in the world. Current research on desertification has primarily concentrated on technical aspects, particularly sand control and management strategies (You et al., 2018). Over 60% of the Belt and Road corridor is situated in semi-arid, arid, desert, or high-altitude regions characterized by extremely fragile ecosystems. Policies and regulations for combating desertification encompass laws and guidelines focused on sand control, soil and water conservation, and the protection of natural resources and the environment. These efforts aim to maintain the ecological and economic productivity of land and resources that are essential for social and human well-being (Huang et al., 2020). While desertification control policies share characteristics with general

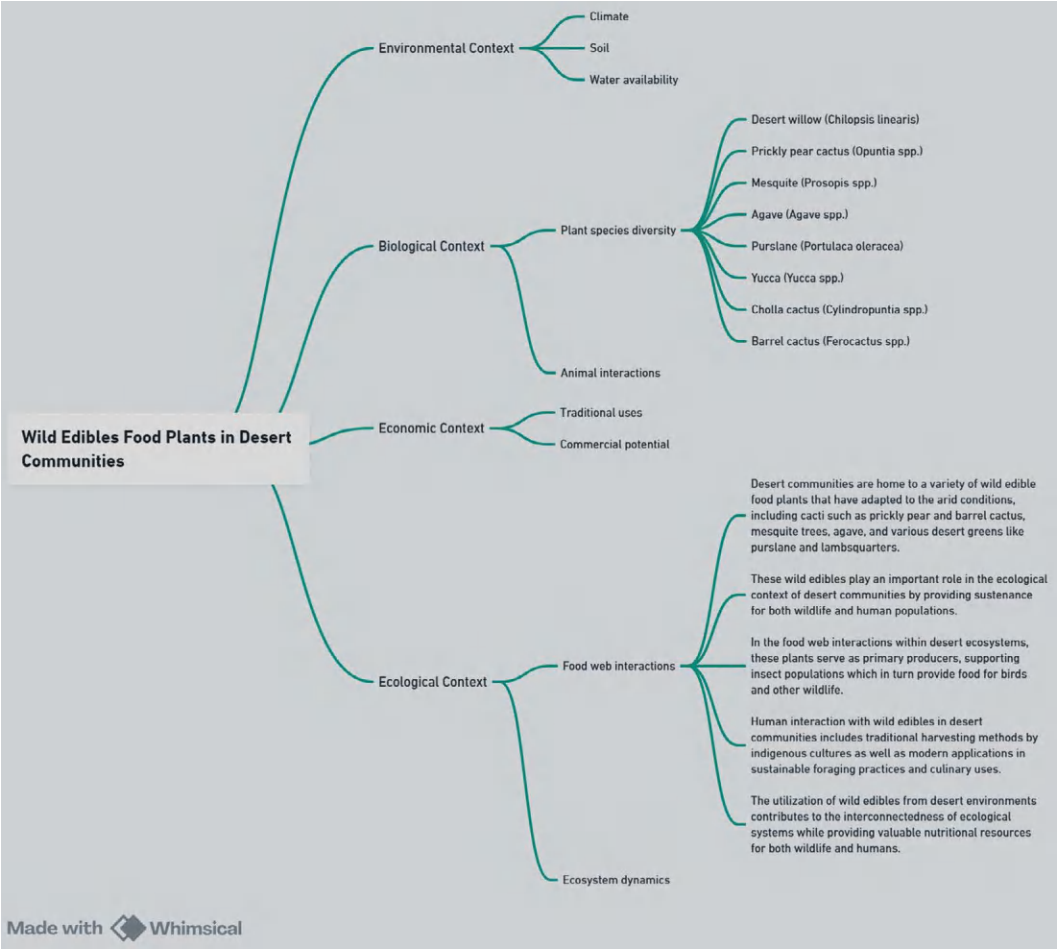

FIGURE 4.1 Conceptual diagram linking environmental, biological, economic, and ecological contexts in desert communities food security.

public policy, they rely on distinct theories and methods due to the complex and long-term nature of desertification processes (Akhtar-Schuster et al., 2011; O'Connor & Ford, 2014; You et al., 2021).

4.2 WEs: NUTRITIONAL VALUE AND DIETARY REQUIREMENTS

WEs play a crucial role in the dietary practices of local communities in desert regions, where harsh environmental conditions challenge conventional agricultural methods. These plants, often resilient to extreme temperatures and arid soils, provide essential nutrients that are vital for sustaining human health. The nutritional value of WEs, including vitamins, minerals, and antioxidants, can significantly contribute to meeting dietary requirements in areas with limited access to conventional food sources. Moreover, traditional knowledge about these plants enhances food security, as local populations have cultivated expertise in identifying, harvesting, and utilizing them sustainably. The role of WEs in the diet of desert communities not only highlights their importance for nutrition but also underscores the need for conservation and sustainable practices that preserve these vital resources in the face of climate change and habitat degradation. This incorporation of nutrition and local ecology is essential for fostering resilience and adaptability in these communities.

The significance of biodiversity in promoting sustainable human and environmental health is widely acknowledged. The Cross Cutting Initiative on Biodiversity for Food and Nutrition, established in 2006 by the Convention on Biological Diversity in collaboration with FAO and Biodiversity International, emphasizes this critical issue: "Immediate action is essential to engage the environmental, agricultural, nutrition, and health sectors" (Frison et al., 2011). Without such coordinated efforts, we risk losing the biodiversity and the valuable resources provided by both domesticated and wild species, which are vital for addressing food security, nutritional deficiencies, and the increasing prevalence of non-communicable diseases (Dop et al., 2020). WEs should be promoted as a natural source of nutraceuticals, offering significant potential to supplement the diets of local populations. To enhance food availability in desert regions characterized by extreme climatic conditions and a limited growing season, the implementation of an agroforestry system is essential. Such a system would facilitate the sustainable utilization of these species while simultaneously increasing their productivity (Batool et al., 2024).

The global community is struggling with numerous challenges related to malnutrition, food insecurity, and famine, driven by poor crop yields, resource scarcity, and the high cost of nutritious food. To address these issues, alternative solutions are urgently needed to meet the dietary requirements of the growing population. WEs represent a promising option; these species are not managed or commercially cultivated but are integral to various cultural, traditional, and heritage practices worldwide (Winstead & Jacobson, 2022). WEs are rich sources of essential nutrients, including carbohydrates, proteins, fats, and minerals, making them vital for nutrition, particularly in developing and underdeveloped regions. Furthermore, their significant nutritional and medicinal properties make them valuable for treating a variety of ailments such as fever, injuries, diarrhea, and toothache. Currently underutilized, WEs are consumed primarily within traditional contexts, and their potential as a key component of the human diet in developed regions remains largely unrecognized. This emphasizes the need for further scientific investigation to promote their widespread acceptance and use globally (Kaur & Roy, 2021). An inventory of WE food resources, along with associated indigenous knowledge, usage methods, and their current status, combined with nutritional evaluations, can provide a viable alternative for enhancing food and nutritional security significantly (Singh et al., 2021). Recently, the growing demand for healthy food and heightened health awareness among the population has sparked renewed global interest in the utilization of WEs. Efforts have also been initiated to mainstream these desert resources, primarily aimed at expanding the food options available to local communities (Talang et al., 2023).

WEs are plants that grow independently without human intervention, relying solely on available resources. These plants are often undervalued due to limited knowledge about their bioactive composition and nutritional or functional potential (Clemente-Villalba et al., 2023). Proximate analysis is commonly employed in food studies to assess the energy, moisture, protein, lipid, ash, and carbohydrate content of the samples. Proteins, lipids, and carbohydrates contribute significantly to the total energy content of an organism, while ash and water contribute to its overall mass. Today, the relationship between the economy and sustainability is increasingly recognized as a critical aspect of societal development (Parimelazhagan & Thangaraj, 2016). WEs also yield valuable substances such as medicinal compounds, fiber, grains, and natural dyes. Numerous widely circulated publications have suggested that the nutraceutical potential of wild plants may equal or even surpass that of commercially cultivated vegetables (Seal et al., 2023). A crucial dietary strategy to combat the rising risk of the double burden of malnutrition among indigenous populations globally is to enhance nutritional and food diversity through the incorporation of various traditional plant-based WE foods (Della et al., 2006). WEs offer essential micronutrients and macronutrients necessary for the body functioning as functional foods that rural communities often utilize to address various ailments and diseases. Moreover, WEs frequently possess superior nutritional quality compared to cultivated varieties (Tharmabalan, 2023).

WEs are abundant in essential nutrients and can enhance dietary diversity, reducing reliance on a limited range of food sources. Moreover, they contribute significantly to income generation

for some local communities. Many WE plants are recognized for their beneficial effects on human health due to their medicinal properties. These plants are often referred to as nutraceutical plants because they offer both nutritional and therapeutic advantages (Anbessa et al., 2024). The health benefits of WEs are largely attributed to their rich content of natural antioxidants, including phenolic compounds, ascorbic acid, tocopherol, carotenoids, and anthocyanins, which can help safeguard against oxidative damage (Santhi et al., 2021). Underutilized WEs hold substantial potential to enhance food security, improve nutrition and health, generate income, provide environmental services, and combat the hidden hunger associated with micronutrient deficiencies (Angami et al., 2024). WEs are identified as minor, neglected, local, orphan, and promising species that have been utilized for centuries for their food, fiber, fodder, oil, and medicinal properties. However, the significance and utilization of these weeds have significantly declined due to factors such as limited supply, short shelf life, unrecognized nutritional values, low consumer awareness, and reputational issues. In terms of food security, many developing countries are grappling with food scarcity (Baas, 2012). Therefore, it has become essential to explore the potential of new plant resources that can contribute to food, medicine, fodder, energy, and other commercial uses, with the goal of alleviating the impacts of hunger and starvation. Some underutilized crops with strong nutritional and medicinal potential, as well as low input requirements, have emerged as a promising solution to this challenge. This situation is exacerbated by the negative effects of increasing human population, rapid urbanization, environmental degradation, and climate change (Peduruhewa et al., 2021).

The pursuit of achieving as many SDGs as possible by the target date of 2030, particularly SDG 2, has driven scientists and practitioners to explore innovative strategies for enhancing the supply of safe and nutritious food for both current and future generations without compromising environmental integrity (FAO, 2014). One emerging approach gaining attention on international agendas is the increased and improved utilization of orphan crops and WE species within agricultural systems, food supply chains, and overall food systems. This involves exploring creative methods to boost consumer demand and appeal for these valuable plants' genetic resources (Borelli et al., 2020). WEs are gaining recognition as valuable food sources due to their nutritional benefits, positive health effects, and innovative applications in haute cuisine. Since these native plants thrive naturally in their environments, they are better adapted to varying climatic conditions and biotic and abiotic stresses (Ray et al., 2020). This adaptability paves the way for their potential cultivation, which often incurs lower costs compared to other commercially cultivated crops. Moreover, the growing consumer demand for sustainable and ecologically labeled natural products has further fueled the recovery and integration of WEs into the market (Pereira et al., 2020; Punchay et al., 2020). WEs are crucial to the livelihoods of rural communities, serving as a vital component of the subsistence strategies for many in developing countries. A significant challenge to human survival, especially in the developing world, is the widening gap between the human population and food supply (Kidane & Kejela, 2021). The extensive cultivation of various crops, coupled with industrial advancements and shifts in lifestyles, has led to the underutilization of WE plant resources (Tahir et al., 2023).

Countries such as Indonesia, Papua New Guinea, and Sri Lanka moderately utilize WEs for food and medicinal purposes. In contrast, nations like India, Malaysia, Nepal, Pakistan, and the Philippines employ these resources extensively (Alemu et al., 2024). The nutraceutical potential of WEs is derived from the biological activity of their secondary metabolites, making them widely utilized in health food preparation, pharmaceuticals, and cosmetics. However, the valuation of WEs is increasingly critical due to concerns about the loss of ethnobotanical knowledge, which is traditionally passed down through generations (Orlandi et al., 2024). Globally, malnutrition presents one of the most significant societal challenges, leading to substantial health, economic, and environmental issues. Many countries are grappling with the dual burden of malnutrition, where undernutrition coexists with being overweight, obesity, and other diet-related non-communicable diseases (Hunter et al., 2019). This issue is particularly acute in sub-Saharan

Africa, where poor diet and malnutrition are prevalent due to a lack of protein, energy foods, and essential micronutrients. Contemporary industrial agriculture and modern global food systems have intensified the decline of many WE plant species, largely due to an over-reliance on monocultures of high-yielding, genetically uniform crops (Akombi et al., 2017). WE plants, which can be harvested from natural environments or cultivated in traditional systems with minimal external inputs, have the potential to diversify diets and address hidden hunger stemming from micronutrient deficiencies (Lykke & Padonou, 2019). Moreover, these WEs are naturally suited to local soil and climates, making them more resilient to environmental stresses than introduced species. Therefore, it is essential to preserve, enhance, and optimize these plants through various silvicultural practices, particularly in resource-poor and arid regions, to support the livelihoods of vulnerable populations who face the challenges of climate variability and degradation (Mokria et al., 2022; Zait & Schwartz, 2018).

The growing global recognition of the fundamental value of WEs, shaped by cultural perspectives and dietary choices, underscores their potential to address malnutrition, enhance dietary diversity, and improve health outcomes. The sustainable practices of WEs that are adapted can serve as a solution that promotes both ecological balance and human well-being. The utilization of their capabilities could transform global nutrition and health landscapes (Anwar et al., 2024). WEs not only contribute to the diversity of global food systems through their nutritional advantages but also support environmentally friendly practices, reducing pressure on over-exploited agricultural lands. Deeply rooted in various cultures as traditional dietary staples, these plants resonate with local food perceptions and preferences. They can effectively combat malnutrition by providing essential micronutrients often lacking in processed foods, and they demonstrate resilience in the face of climate changes (Belhaj et al., 2021). Plant biodiversity is essential for global food and nutrition security. The consumption of WEs dates back to prehistoric times and remains important for some traditional communities today (Gee et al., 2020). However, the significance and reliance on WEs vary greatly across different cultures. In many traditional societies, WEs serve as a complement to staple foods, enhancing dietary diversity and nutritional balance (Ulian et al., 2020). In more contemporary contexts, such as in Europe, the consumption of WEs is influenced by modern perspectives on wellness, health, and fitness, as well as cultural and ethical considerations (Bharucha & Pretty, 2010). In both scenarios, the practice of consuming WEs is intertwined with cultural identity and reflects the deep connections between communities, their land, and the TEK of their environments and lifestyles (Afolayan & Jimoh, 2009; León-Lobos et al., 2022).

Food serves as a fundamental link between humans and the environment, shaping our interactions with other living beings and embedding intangible cultural legacies. Over 7,000 plant species are considered edible, many of which are integral to the traditional gastronomic heritage of various cultures and have the potential to enhance food security and promote sustainable agriculture globally (Padulosi et al., 2011). However, the modern human diet relies heavily on just ten species, a trend that emerged from the Green Revolution. This movement prioritized high-yield commercial hybrids over traditional landraces and wild species, resulting in several negative consequences (Kor et al., 2021). Interest in local edible plants declined, alongside a waning focus on the health of ecosystems that support them, leading to their degradation. Moreover, the increasing demand for a limited range of natural resources and unsustainable cultivation practices have contributed to the rapid depletion of natural populations of WEs (Kalamandeen et al., 2018). In response to these challenges, international policy frameworks have increasingly sought to integrate biodiversity protection with sustainable development over the past few decades. There has been a concerted effort to revitalize and promote the use of orphan crops and WEs (Hunter et al., 2019). More than 50 years after the Green Revolution, neglected and underutilized species have emerged as vital resources for fostering sustainable livelihoods and mitigating environmental degradation. WEs also carry significant biocultural values, as they are intricately linked to local agricultural practices and culinary traditions, embodying the essential relationship between nature and culture (Gori et al., 2022).

4.3 KNOWLEDGE, MARKETING, AND FINANCE OF DESERT WEs

Desert WE food species offer a unique and sustainable source of nutrition, often overlooked in traditional food systems. These plants, adapted to harsh environments, are rich in vitamins, minerals, and other nutrients, making them valuable for both local communities and broader markets. Understanding their ecological roles and benefits can enhance biodiversity while supporting local economies. Effective marketing strategies can raise awareness of these species, highlighting their cultural significance and health benefits. Moreover, integrating financial models that support sustainable harvesting, and cultivation can ensure these resources are preserved for future generations. The development of knowledge about WEs can promote healthier diets and encourage sustainable practices in desert regions.

Organic certification can serve as a crucial tool for ensuring that consumers can purchase WEs produced in environmentally friendly ways, aligning with their values (Turtiainen & Nuutinen, 2012). Moreover, enhancing awareness of wild ingredients in organic foods and the organic certification process for wild food plants would help elevate the profile of organic wild plant food value chains in political and public discussions (Schunko & Vogl, 2020). Labeling wild ingredients on final products would facilitate the identification of these plants throughout the value chain, supporting data collection on the gathering and trading of organic WEs. This data generation is essential for accurately understanding and tracing the true quantitative value of wild food plants (Schunko & Vogl, 2018). Traditional WE foods represent locally accessible resources for indigenous communities, grounded in long-standing traditional knowledge and cultivated through traditional farming systems or foraged from the wild (Kuhnlein, 2009). WE foods have been consumed for generations or introduced in the past, becoming socially and culturally accepted as part of local cuisine. Key sociodemographic factors, such as gender, age, education level, and language significantly influence individual knowledge of these traditions. However, sociocultural changes have affected knowledge transmission, resulting in younger generations and more educated women being less familiar with edible plants. Preserving knowledge about these plant resources is crucial for maintaining nutritional and health benefits (Pascual-Mendoza et al., 2022).

Rural communities rely heavily on WE food plants as dietary supplements, providing nutritionally dense options that sustain them during periods of food scarcity and often enhancing local dishes (Mujuru et al., 2020). Communities near biodiversity hotspots utilize WEs and medicinal plants year-round, incorporating them into their diets as fruits, vegetables, teas, snacks, alcoholic and non-alcoholic beverages, and jams. The collection of wild food typically involves all family members, though women and girls play a significant role in gathering WE resources for household consumption (Shumsky et al., 2014). The cultivation of indigenous fruits in rural desert communities is crucial for enhancing household livelihoods. This emphasizes the necessity to reevaluate the prevailing policy narrative that often overlooks these indigenous plants. A focused initiative is required to boost their productivity and commercialization, serving as a key strategy for improving rural livelihoods and driving transformation (Olowo et al., 2022). Hunger, food insecurity, and malnutrition represent significant global challenges, as highlighted by the SDGs aimed at eradicating hunger, achieving food security, and enhancing nutrition by 2030 (Kouyaté et al., 2021). To address these issues effectively, it is essential to engage multidisciplinary research teams, including plant breeders, botanists, molecular biologists, food scientists, and horticulturists. Moreover, governments and international stakeholders must provide incentives to promote the domestication, commercialization, and agro-processing of underutilized WE trees, paving the way for future economic prosperity (Omotayo & Aremu, 2020).

An increasing body of scientific evidence emphasizes the significance of traditional foods in enhancing food and nutrient security. However, challenges remain in their wider adoption and popularization. By adhering to the principles of "free, prior, and informed consent" and access and benefit sharing, traditional foods that provide health and environmental benefits can

serve as key avenues for transforming food systems. It is essential to thoroughly explore these opportunities (Kennedy et al., 2022). Indigenous WEs are consumed daily in some form by at least one in seven people globally. Many of these foods are rich in essential nutrients and have the potential to enhance dietary quality and nutrition, especially for low-income households (Oduor et al., 2023). The use of essential WEs has been extensively documented across various regions, particularly in contexts of food insecurity and among low-income communities (Hankiso et al., 2023). WE plants serve as a vital component of global food systems, often referred to as the wild supermarket, supporting numerous populations during environmental shocks, droughts, and famines (Tebkew et al., 2018). This vital traditional knowledge regarding the gathering and consumption of WEs is eroding rapidly among younger generations, largely due to the influence of fast food, modernization, and globalization. Consequently, it is essential to implement effective strategies to protect both traditional plants and the associated knowledge and practices, as well as the cultural heritage they embody. Furthermore, these efforts can contribute to food security and enhance public health through the utilization of local wild foods (Abdullah et al., 2021).

There is a growing demand for nutrient-dense fruits to enhance human nutritional and metabolic health. The production of commercial WE fruit crops is increasingly reliant on external inputs to manage losses from biotic and abiotic stresses (Haddad et al., 2016). A diverse range of underutilized crops, which are not widely cultivated or traded, are primarily grown, commercialized, and consumed locally. These underutilized fruits offer several advantages, including ease of cultivation, hardiness, and resilience to climate change, in contrast to the major commercially produced WE crops (Meena et al., 2022). WE plants do not require irrigation or fertilizers and demonstrate strong potential for cultivation on marginal lands. They are regarded as a healthy alternative to commercial fruits and vegetables, which may contain pesticide residues and other chemicals from their production processes. Furthermore, consumers frequently favor foods with distinct geographic origins and connections to indigenous cultures and culinary traditions (Aguilera & Toledo, 2024). Developing new WE crops diversifies diets and markets and stimulate the local economy, thereby enhancing and sustaining the livelihoods and human capital of vulnerable and disadvantaged rural communities regarding new WE crops from indigenous food and non-food trees. It also diversifies farming systems and creates niches for fostering biodiversity both above and below ground (Leakey et al., 2021).

WE species play a crucial role in enhancing food security and diversifying household income. This can be achieved by strengthening botanical knowledge, collecting germplasm, and advancing genetic improvement. It is essential to increase the availability of high-quality planting materials and promote on-farm cultivation through agroforestry systems, which will facilitate the identification and selection of preferred WE species (Abdella et al., 2023). Furthermore, WE species are essential for the development of new food crops through domestication and serve as a vital genetic resource for enhancing the productivity of cultivated varieties (Giday & Teklehaymanot, 2023). Products derived from WE species are widely traded in informal local markets within the region, contributing up to 20% of overall household income (Heubach et al., 2011). Moreover, in specific political and social contexts, market integration and commercialization aimed at high-income export markets can offer further income opportunities for participants in the WE value chains (Leite et al., 2024). Most WE plants grow in village environments, making village residents the primary consumers of these crops. Many individuals, particularly those in economically disadvantaged situations, rely heavily on wild leafy vegetables, fruits, and flowers. Therefore, it is essential to understand the extent of dependency on WEs and their economic benefits as dietary alternatives for future food sources. However, agricultural yields have struggled to meet the demands of a rapidly growing population. To address this challenge, increasing the incorporation of WEs into the diet is vital. Evaluating the dependency on and economic value of lesser-known WEs is critical for understanding their role in food security (Harisha et al., 2021).

4.4 WEs: FUNCTIONAL FOODS AND HEALTH

Plants have served as both food and medicine since ancient times, and their significance in contemporary society is undeniable. Today, many consumers are increasingly aware of the link between nutrition and health, particularly concerning functional foods and nutraceuticals. The global market for functional foods and nutraceuticals is expanding at a pace that surpasses that of traditional processed food products (Pinela et al., 2016). Desert regions are endowed with valuable natural resources, particularly arid fruits and vegetables. Indigenous communities utilize these arid fruits as a primary food source, often imbued with cultural significance. Transforming these traditionally important arid foods into more functional and convenient products can enhance livelihood security for populations globally. Consequently, studies have explored the prospects for value addition, including analysis of their nutritional composition, phytochemical content, and antioxidant activities (Mann et al., 2013). WE plants hold significant importance in both historical and contemporary human societies. Their utilization reflects evolutionary trends, ongoing interactions between humans and nature, relevant traditional knowledge, and cultural heritage. A conceptual framework for understanding WE plants encompasses their contributions to human diets and daily life, emphasizing nutritional and cultural value, food sovereignty and security, and the substantial legacy they provide for future generations (Carvalho & Barata, 2016).

The demand for visually appealing and high-quality food continues to grow. This increasing interest in functional foods and nutraceuticals has intensified the search for new food sources that positively impact human health. Among these, WE flowers have emerged as a novel nutritional option. These non-toxic flowers add color, texture, and freshness to dishes, while also serving as potential sources of beneficial phytochemicals. Rop et al. (2012) suggested that WE flowers could enhance global demand for more attractive and flavorful foods, while also improving the nutritional profile of culinary creations. Kinupp et al. (2021) noted that plants with WE blossoms enhance visual appeal, enrich the surrounding environment, optimize the use of local flora, diversify menus and nutrient intake, and create new income opportunities. Furthermore, WE flowers are recognized as excellent sources of nutritional and phytochemical compounds, with their high antioxidant content being particularly noteworthy (Loizzo et al., 2016; Navarro-González et al., 2014). WEs have historically played a crucial role in complementing staple foods by providing essential trace elements, vitamins, and minerals necessary for a balanced diet, and they hold the potential to do so again in the future. The consumption of WEs can offer health benefits due to their high antioxidant content and nutritional value, as well as their appealing sensory qualities. Moreover, WEs can enhance ingredient diversity in contemporary cuisine (Romojaro et al., 2013).

WEs are vital for the sustenance of many human populations.. WEs are frequently examined from phytochemical and pharmacological perspectives due to their nutraceutical value (Asprilla-Perea & Díaz-Puente, 2019). Understanding the benefits of incorporating WEs into diets is essential, as they typically offer a more concentrated nutritional profile and are easy to cultivate since they grow wild. Moreover, WEs help preserve local knowledge regarding WE food species, including relatives of landraces and other cultivated crops. Thus, they not only provide dietary advantages but also support traditional knowledge and associated genetic resources (Casas et al., 2024). WE functional foods contain health-promoting components that are beneficial for human health and may aid in disease prevention or treatment. The demand for WE functional foods is increasing not only in developed regions but also in developing areas, driven by greater consumer awareness of the impact of food on health (Olaiya et al., 2016). WE functional foods are abundant sources of bioactive compounds, particularly antioxidants, which play a critical role in vivo by modulating disease development through the inhibition of reactive oxygen species-mediated reactions associated with conditions such as cancer, diabetes, and coronary heart disease (Ashaolu & Adeyeye, 2024). Many under-researched WE plants exist in desert regions worldwide. These plants may serve as promising candidates for enhancing food security while delivering valuable bioactive compounds through diet (Jaradat, 2020). Generally, the bioactive components in foods exhibit synergistic, additive, or

antagonistic interactions. For WE plants from arid zones, scientific validation supports traditional practices of consuming these foods in combination. Such indigenous food pairings derived from desert flora could provide valuable insights for the development of sustainable functional foods and nutraceuticals (Joshi et al., 2024).

WEs as functional foods of desert regions and their classification are primarily based on the natural properties of the ingredients themselves. Key considerations include health benefits, functionalities, and methods of consumption. Ingredients can qualify as WE functional foods in their natural state (Danzomo et al., 2024). Alternatively, they may be regarded as functional foods through: (1) enrichment with health-promoting nutrients or components; (2) elimination of harmful components; (3) modification using technologies such as fermentation or thermal treatment to enhance health benefits; or (4) any combination of these approaches (Hui-Yan & Sarbini, 2024). Rural desert inhabitants have a long-standing tradition of foraging a wide variety of WE fruits. This practice is largely driven by the fruits' appealing flavors, cultural significance, and their role as dietary supplements to mitigate food scarcity (Balemie & Kebebew, 2006). Often referred to as famine or hunger foods, WE fruits are recognized for their potential to contribute to both household food security and economic stability. Many communities worldwide continue to rely on WE plants for their livelihoods. Various wild fruits have been utilized for centuries throughout the arid regions of the Indian subcontinent due to their nutritional and therapeutic properties. Incorporating these compounds into dietary patterns can enhance essential nutrients and introduce unique bioactive molecules that may significantly impact human health (Ngurthankhumi et al., 2024).

In recent years, there has been a growing concern over healthy diets and nutrition, leading to an increased interest in naturally sourced foods, particularly various fruits, and vegetables, due to their rich nutritional profiles, which include antioxidants, minerals, and vitamins (Sanz et al., 2021). Wild fruits are recognized as a significant source of nutrients that can benefit our health. With rapid globalization, fruits are not only consumed as part of a diet but are also utilized in the development of various food products, cosmetics, and pharmaceuticals. Tropical WE fruits can be broadly categorized into two groups: major tropical WE fruits and minor tropical WE fruits. Major tropical WE fruits are commonly produced in tropical and, when climate permits, subtropical countries (Sarkar et al., 2023). WE fruits are well-known in both local and international markets and have established production and export statistics globally. They are characterized by their consistent and early production, longer shelf life, favorable shipping qualities, adaptability to different environments, and ease of propagation and distribution (Altendorf, 2018). The term "WE foods" refers to food sources that are available in their natural state, without cultivation for plants or raising for animals. Terrestrial and marine WE plants and animals remain primary food sources for hunter-gatherer and foraging cultures globally (Motti, 2022). Approximately 90–100 WE plant species are essential to the livelihoods of many rural communities in regions like Asia and Africa, including countries such as India, Ethiopia, and Kenya. WE foods play a vital role in nutrition, food security, and environmental conservation, and they often provide communities with a source of income to purchase other food items (Yang et al., 2020). WE plants do not require irrigation or fertilizers, demonstrating strong potential for cultivation on marginal lands. Moreover, WE foods are viewed as healthier alternatives to commercially produced fruits and vegetables, which may contain pesticide and chemical residues. Consumers also tend to favor foods that have unique geographic origins and connections to indigenous cultures and culinary traditions (Aguilera & Toledo, 2024).

Since ancient times, WE foods and natural products have been utilized globally as traditional medicine, valued for their high therapeutic effectiveness in treating various ailments. Today, the use of natural products is recognized for its high biocompatibility and minimal side effects. WE foods are natural sources and have played a significant role in the development of approximately 50% of approved pharmaceuticals on the market (Saleem et al., 2024). As the interest in sustainable and health-promoting WE food sources rises, cacti are increasingly recognized as valuable functional food ingredients. Their adaptation to harsh environmental conditions makes them ideal for cultivation in regions with limited water resources (Monteiro et al., 2023). Cactus food plants possess a

unique blend of nutritional and functional attributes, including high dietary fiber, a diverse range of phytochemicals, and low caloric content, presenting significant opportunities for the food industry (de Albuquerque et al., 2022). The manufacture of new functional WE foods aimed at disease prevention represents a significant modern-day research challenge. Many traditional foods already function as effective WE foods, as their preparation methods are well-established in their countries of origin, where they are consumed for their health benefits (Gok, 2023). The therapeutic effectiveness of WE foods is influenced by multiple factors, including consumption levels, the type and concentration of nutraceuticals, minerals, and phytochemicals present as active components. The bioavailability of these constituents in conventional medicines is affected by the disease etiopathology, the physiological state of the consumer, behavioral patterns, and genetic factors (Pasdaran et al., 2023). The global food system relies heavily on a narrow range of WE plant species. While plants with inadequate nutritional value are overproduced, a diverse array of nutrient-rich WE species that were commonly used in the past has been largely overlooked (Kim & Baik, 2015). Relying on a limited number of crops has significant negative implications for nutrition and food security. Despite being under-researched, underutilized WE plants are gradually gaining attention. These plants offer superior nutritional profiles and hold great potential to enhance food and nutrition security, as well as promote sustainability (Knez et al., 2024; Rymbai et al., 2023).

WE plants are gaining significant attention from scientists, governments, and local communities in arid rural areas due to their potential as novel nutraceutical sources and their contribution to food security. Understanding their nutritional value is becoming increasingly important. WE foods offer additional benefits for human physiology and metabolic functions, including antioxidant properties that play a crucial role in disease prevention and the promotion of overall health (Coban et al., 2021). WE plants are rich in minerals essential for a healthy human diet, as well as various primary and secondary metabolites that impact nutrition and health. While secondary metabolites are not vital for the overall growth or functioning of WE plants, they exhibit biological activity that makes them valuable as ingredients in both traditional and modern medicines (Samtiya et al., 2021). WE fruits, in particular, are abundant in micronutrients such as magnesium, calcium, and potassium, as well as bioactive compounds including phytochemicals like polyphenols, dietary fiber, carotenoids, and vitamins (Gürbüz et al., 2018).

4.5 HEALTHY SUSTAINABLE DIETS OF DESERT WEs

The predictable population growth is anticipated to significantly increase food demand, particularly in impoverished regions of the developing world. Ongoing droughts typically result in reduced food production, and when combined with rising population numbers, this leads to food and nutritional insecurity, with the most vulnerable populations suffering the most. Moreover, food insecurity is worsened by postharvest losses. Globally, it is estimated that approximately 1.3 billion tons of food – equivalent to one-third of all food produced for human consumption – are wasted or lost each year before reaching consumers. The report highlights that developing nations, particularly in sub-Saharan Africa and South/Southeast Asia, experience postharvest losses roughly 10% lower per capita than those in industrialized countries. Various factors contribute to postharvest losses, including inadequate infrastructure, insufficient storage facilities, ineffective marketing strategies, and limitations in financial resources, technical expertise, and packaging solutions. These losses affect both cultivated and wild food crops (FAO, 2011). The pursuit of increasing food production with fewer resources has become a key focus in food security research. While food security is typically defined by factors such as availability, utilization, and access, these criteria may not fully address nutritional needs. Moreover, food availability does not automatically guarantee access to a healthy and balanced diet (Bvenura & Sivakumar, 2017). Current statistics reveal a substantial array of plant food resources that could be harnessed to combat food and nutrition insecurity. However, if underutilized WEs are overlooked, they risk extinction as traditional knowledge about them fades away with the few individuals who possess

it. Given this vast potential of available plant food resources, it is concerning that undernourishment continues to be a significant global challenge (Charrondière et al., 2013).

A variety of factors, including subsistence methods, economic conditions, ecological contexts, and cultural attitudes, influence how people acquire knowledge and utilize WE plants (Luczaj et al., 2012). It is widely recognized that urban populations tend to use fewer WE plants compared to those in rural areas, primarily due to restricted access to these resources. Furthermore, within specific cultures, gender and age can play significant roles in shaping the knowledge and utilization of wild food resources (Kujawska & Łuczaj, 2015). Mineral nutrition is a crucial factor for the healthy growth of organisms, and WEs are a readily available source of essential minerals (El-Amier & Abdullah, 2015). Recently, there has been a growing recognition of the significance of WE plants in rural economies, as they have the potential to serve as valuable food sources. Integrating WEs into dietary strategies could be an effective approach to addressing food insecurity (Negi & Subramani, 2015). The SDGs serve as a cohesive global agenda that all countries are expected to pursue. Among these goals, SDG 2 aims to ensure food security and nutrition through sustainable food systems that include WEs. However, realizing this goal is fraught with challenges due to current global food production and consumption practices. Existing trends in diets and the food systems that generate them indicate that they are neither healthy nor sustainable, posing significant obstacles to achieving SDG 2 (Fanzo, 2019). A healthy and sustainable diet should reduce the intake of energy-dense, highly processed, and packaged foods, prioritize plant-based WE foods over animal-derived products, and encourage adherence to recommended daily energy intake levels. Sustainable diets that incorporate WEs enhance food and nutrition security, have minimal environmental impact, and support the health of current and future generations (Alsaffar, 2016).

WE plants play a crucial role in human health and nutrition, as they provide a wide range of essential nutrients. Various parts of these plants, such as leaves, roots, stems, flowers, and fruits, not only offer nutritional benefits but also possess medicinal properties. Many WE food-bearing plants, whether seasonal, annual, or perennial, can help alleviate pressure on conventional agriculture. However, the consumption of WE foods is often limited to populations residing in regions where they naturally grow (Mishra et al., 2015). WE plants represent an abundant yet often underutilized food source that can enhance dietary diversity and vegetable consumption, particularly in regions with limited access to fresh produce (Stark et al., 2019). The tradition of using WE food plants for their nutraceutical benefits serving as both food and medicine is under threat, and the transfer of traditional knowledge from older generations to younger ones is diminishing. Consequently, it is essential to collect information on the cultural significance and consumption patterns of WE foods (Khan et al., 2024; Wang et al., 2020). Recent assessments highlight the significance of sustainable plant-based WE diets in addressing the adverse effects of industrial agriculture and mitigating climate change (Cleveland & Gee, 2017). Recent global climatic and socioeconomic changes have renewed attention on wild foods and foraging practices, positioning them as a key element of the sustainability agenda. These practices could promote a more balanced use of biological resources while also offering potential benefits for human health (Ivanova et al., 2023).

The human body is unable to synthesize minerals and vitamins, necessitating their intake through food. WE plants are acknowledged for their health benefits in combating various chronic disorders (Fratianni et al., 2024). They are rich in fiber, protein, and numerous minerals, and they contain significant amounts of bioactive compounds such as polyphenols, vitamins, tocols, and carotenoids, which are crucial for both therapeutic and nutritional purposes (Clemente-Villalba et al., 2023). The global population, currently around 8.2 billion, is projected to rise to approximately 8.5 billion by 2030. This anticipated increase in population is expected to significantly drive up food demand, particularly in poorer developing countries (Bvenura & Sivakumar, 2017). Ongoing droughts typically result in decreased food production, and when combined with population growth, this leads to heightened food and nutrition insecurity, with the most vulnerable populations suffering the most. Furthermore, food insecurity is further compounded by postharvest losses (Masarirambi et al., 2010). Humans rely on terrestrial and marine ecosystems for their food supplies, encompassing both

plants and animals. It is estimated that there are between 300,000 and 500,000 species of higher plants, with at least 250,000 identified and documented. (Wang & Zhang, 2011). According to the same report, about 30 major crops are responsible for feeding the global population, providing 95% of dietary energy and protein. In contrast, minor and underutilized species, including wild fruits and vegetables, play a crucial role both nutritionally and culturally in many societies (Charrondière et al., 2013).

The global population is projected to reach 9 billion by 2050, and the capacity of our current food system to meet future food demands remains uncertain. One of the most significant challenges of our time is ensuring that all individuals have access to sufficient and nutritious food that is produced in an environmentally and socio-culturally sustainable manner (Vinceti et al., 2013). Sustainable WE diets have been proposed as a comprehensive framework to address the need for adequate nutrition amidst various global challenges, including the reduction of poverty and hunger, the improvement of environmental health, the enhancement of human well-being and health, and the strengthening of local food networks, sustainable livelihoods, and cultural heritage (Hunter & Fanzo, 2013). Current discussions emphasize that sustainable food systems can be promoted through the careful and relevant use of natural resources (Heywood, 2013). The traditional practices of foraging, cooking, and consuming wild food plants that are readily available in specific environments have historically been vital for ensuring food security and sovereignty in many local communities. Over the past decade, research has increasingly focused on the bio-cultural heritage associated with WE plants, as well as neglected and underutilized species. This diversification of diets and traditional ingredients is recognized as a crucial strategy for addressing malnutrition and hunger (Pieroni et al., 2021). Variations in the categorization and use of WE food plants among different ethnic and linguistic groups inhabiting the same environment exemplify the dual nature of biocultural diversity, which tends to be more pronounced at ecological and cultural boundaries (Pieroni et al., 2020). WE flora has the potential to enhance emerging horticultural sectors, such as vertical farming and microgreens production. Furthermore, the nutrient content and health benefits of many wild food plants identified in this study can help meet consumer demand for functional foods (Redžić & Ferrier, 2014). The consumption of WE plants has often been overlooked and marginalized within modern agricultural systems, typically regarded as a fallback option to supplement otherwise inadequate diets during periods of food scarcity caused by conflict or crop failure. The use of WE plants is intrinsically linked to environmental conservation. In this context, preserving and transmitting local traditions serves to maintain the vital connection between communities and their surrounding environment, where traditional knowledge has been developed and practiced (Baldi et al., 2022).

In recent years, evolving consumer demands and market interest in innovative product varieties have led to a heightened focus on research aimed at enhancing the technological attributes of agricultural products. Among the desired characteristics, there is a particular emphasis on those that support the health benefits of these products. This shift is especially significant in more developed countries, where modern dietary patterns have contributed to the rise of chronic degenerative diseases (Bufano, 2021). WE plants thus represent an invaluable reservoir of genetic diversity and biological variety at the farm level. These species and varieties exhibit considerable genetic variation and demonstrate resilience to droughts and climate change, as well as resistance to pests and diseases, having successfully navigated the domestication bottleneck (Dempewolf et al., 2014). Functional foods, or WE foods that offer not only essential nutritional and energy needs but also additional physiological benefits, have garnered significant attention in recent years. The functionality of a food typically depends on its specific constituents, leading consumers to increasingly prefer natural ingredients derived from plants (Hussain et al., 2023). In developing countries, many individuals struggle to meet their daily nutritional requirements, often resulting in deficiencies in one or more micronutrients. Moreover, those residing in arid regions of developing countries rely on wild resources, such as WE plants and mushrooms, as vital food sources (Mukhtar, 2016). Foraging is an essential socioecological practice for many local communities worldwide. Rural and remote

communities actively engage in foraging for WE plants. Residents of desert areas are particularly susceptible to food insecurity, making foraging a critical ecological adaptation during periods of famine or food shortages. Policymakers should prioritize the preservation of this food heritage in future development programs (Khalid et al., 2023). WE plants can rightly be regarded as an ecosystem service, or even a suite of ecosystem services, since "wild edible plants" serves as an umbrella term encompassing a diverse range of tangible goods, each representing a distinct service. These goods (species and their parts) lack a standardized metric for comparison, meaning that a specific quantity in kilograms of one type of good is not equivalent to the same quantity of another type (Vári et al., 2020). Documenting desert WE food resources among linguistic and cultural minorities is crucial for implementing strategies that preserve food biocultural heritage. Furthermore, interdisciplinary research on the cultural heritage of desert WE foods is essential for advancing both environmental and social sustainability (Abdul Aziz et al., 2020; Alhobishi et al., 2023).

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5 Desert WEs, Climate Change, and Ecological Transition

5.1 DESERT WILD EDIBLES CAN MEET THE NEEDS OF FUTURE GENERATIONS

Desert wild edibles (WEs) are plants and fruits native to arid environments, and they offer a sustainable food source that can support future generations. These plants are often well-adapted to harsh conditions, requiring minimal water and care. Examples include the prickly pear cactus, mesquite beans, and wild amaranth, all rich in nutrients and versatile for cooking. Utilizing desert WEs can help reduce reliance on conventional agriculture, which often demands significant water and land resources. Moreover, many of these plants thrive in poor soil conditions, making them ideal for areas affected by climate change. Harvesting and consuming these wild foods not only provides nourishment but also promotes biodiversity and ecosystem health. By incorporating desert WEs into our diets, we can enhance food security and encourage sustainable practices. Educating communities about these resources fosters a deeper connection to local ecosystems and encourages responsible foraging. As we face challenges related to food supply and environmental sustainability, recognizing the potential of desert WEs can play a crucial role in creating resilient food systems for future generations. Embracing these native plants not only supports our health but also preserves the delicate balance of desert ecosystems.

Humans globally have relied on WE growing plants for their diets for hundreds of thousands of years, and many still depend on these species to fulfill a portion of their daily nutritional requirements. WEs encompass roots and underground parts, shoots and leafy greens, berries and other fleshy fruits, grains, nuts, seeds, mushrooms, lichens, algae, and various other species. Utilizing these resources necessitates specific cultural knowledge about harvesting techniques, preparation methods, cooking practices, and other processing techniques (Turner et al., 2011). As climate change intensifies, many staple food crops, such as rice, are increasingly vulnerable to rising temperatures, resulting in unpredictable yields and unexpected disease outbreaks (Lynch et al., 2021). Consequently, humanity is compelled to seek alternative WE food options, primarily from indigenous plants that require less water and minimize the need for chemical fertilizers and pesticides. In recent decades, the life cycle of WE foods has grown to encompass manufacturing, packaging, long-distance transportation, storage, and waste generation, resulting in significant environmental costs associated with food production (Joshi et al., 2024).

The average use of WE foods among agricultural and foraging communities in 22 countries across Asia and Africa, based on 36 studies, ranges from 90 to 100 species per location. Cumulatively, estimates for individual countries can reach between 300 and 800 species, as seen in India, Ethiopia, and Kenya. Indigenous communities in both industrialized and developing nations utilize an average of 120 wild species per community. Many of these WE foods are actively managed, highlighting the misconception that agriculture and wild gathering are entirely separate; hunter-gatherers and foragers often cultivate and manage their environments, while agriculturalists incorporate various wild plants and animals into their practices (Bharucha & Pretty, 2010). However, access to WE food sources is diminishing as natural habitats face increasing pressures from development, conservation exclusions, and agricultural

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expansion. Despite their significance, wild foods are often overlooked in official economic statistics regarding natural resources. It is evident that wild plants and animals continue to represent a substantial portion of the global food supply, and as agricultural productivity faces mounting challenges, their importance is likely to increase amidst various social and ecological pressures (Erikson et al., 2008).

Despite the vast diversity of plant species in our world, only a limited number have been cultivated in desert areas for human consumption. This highlights that many plants remain unexploited and undomesticated (Blanco-Salas et al., 2019). WE plants represent a category of underutilized resources, frequently consumed during periods of food scarcity, poverty, adverse weather conditions, or political instability. However, various environmental challenges are contributing to the decline of WE plants and the associated indigenous knowledge (Asfaw et al., 2023). In the past century, dietary diversity has diminished due to an over-reliance on specific cereal WE crops, even though a wide array of edible species remains available. The longstanding tradition of utilizing underappreciated WE flora could be integrated into food policies to diversify diets and improve nutritional outcomes. This could include initiatives under National Nutrition Mission programs, promoting cultivation in nutrition or kitchen gardens, and incorporating these species into mid-day meal programs or similar initiatives (Ray & Ray, 2023). Preserving practices and knowledge related to WEs is crucial not only for safeguarding local biocultural diversity but also for supplying potential functional and nutritious resources that contribute to food security and future economic development (Fang et al., 2024). Fostering interest in nature and biodiversity among younger generations, along with implementing local policies to raise public awareness, is highly recommended (Teixidor-Toneu et al., 2023).

Today, there is a growing trend among humankind to embrace a natural and healthy lifestyle. WE plants are recognized for their medicinal and nutritional richness, gaining unprecedented value in the current context. These plants encompass a diverse range of species that are often underexplored by modern science (Bhutia et al., 2018). The worth of a WE plant species should reflect its nutraceutical potential and its role in supporting biodiversity. Many of these species remain poorly understood, with insufficient documentation on their population dynamics and conservation requirements. Therefore, there is significant potential for this emerging field of study, particularly when integrating traditional knowledge into research and quality enhancement, especially in light of global climatic events that threaten the survival of WE plant species (Abha Manohar et al., 2023). WEs are valuable for developing novel food crops through domestication and serve as a genetic resource pool essential for enhancing cultivar yields (Beyene et al., 2020). Globally, many people depend on these plants during severe food shortages caused by challenges such as drought and poor harvests, particularly in developing countries. Unemployed women living in rural desert areas are often the primary meal preparers for their families; therefore, during times of reduced household income, they are more likely to revert to utilizing WEs (Fikir et al., 2016).

WE plants play a crucial role in addressing challenges related to developing crop varieties that are resistant to pests and diseases. They also aid in identifying new varieties that can adapt to changing climatic conditions, such as drought, extreme temperatures, and frost (Borelli et al., 2020; Vorstenbosch et al., 2017). In many remote areas, emphasizing traditional WE plant foraging is essential for understanding its contribution to food system sustainability, potential health benefits, and the preservation of key elements of local food heritage (Sulaiman et al., 2023). Ethnic knowledge encompasses a variety of WE plants that remain largely unexplored by modern science. Food can serve medicinal purposes when consumed wisely. The global nutraceutical market is rapidly expanding and play a role in reducing the risk of chronic lifestyle-related diseases by modulating metabolism. This is particularly pertinent today, as globalization and economic development have negatively impacted dietary habits, raising concerns about healthy living (Guzo et al., 2023). A systematic approach is necessary to address the many misconceptions and duplicate products that exist in this industry. To enhance human well-being and mitigate

these misconceptions, it is vital to support scientific validation and popularize this concept. As people increasingly seek natural and healthy lifestyles, the term "nutraceutical" is frequently utilized in marketing diverse products. Consequently, there is significant potential for this emerging field, particularly in integrating traditional knowledge of WEs into research and quality enhancement (Manohar et al., 2025).

The recent increase in global malnutrition and reliance on a limited number of crops underscores the significance of WEs and other neglected or underutilized species in diversifying diets, enhancing nutrition, and promoting a more sustainable food system (Ulian et al., 2020). Investigating the uses of WEs that are vital to rural desert communities provides valuable insights into the benefits of a biodiverse landscape for these local populations (Faruk et al., 2024). The simplification and reduction in dietary diversity associated with globalization have resulted in wild food systems that are low in nutritional value but high in caloric content. Integrating indigenous knowledge could support the sustainable management of wild foods while addressing the needs of arid desert communities (Harisha et al., 2023). Globally, billions of people rely on WE species to meet their daily needs. It is essential to understand the current state of global biodiversity and the role of wild species in promoting ecosystem resilience to ensure the sustainability of the planet and the well-being of future generations (Priyadarshini & Bundela, 2023). The promotion of WEs can play a significant role in combating hidden hunger and malnutrition, as they provide an affordable source of locally available, nutrient-rich food. It is essential to protect the genetic diversity of wild food plants (WFPs), and various crop improvement programs should be implemented to enhance their desirable traits. Effectively exploring the diversity of WEs can directly contribute to achieving the goal of zero hunger by 2030 (Thattantavide et al., 2023).

5.2 GLOBAL DESERT WEs: NUTRITIONAL INITIATIVES FOR A HEALTHIER FOOD SYSTEM

Recent global initiatives on WE nutrition have proposed actions to transform food systems, aiming to enhance food environments and improve food choices. The initiatives increasingly emphasize integrated approaches that address food systems and environments, along with their impact on diets, nutrition, and overall health (Reyes et al., 2021). Sustainable WE diets are characterized by their protection and respect for biodiversity and ecosystems, cultural acceptability, accessibility, economic fairness, affordability, nutritional adequacy, safety, and health (Vogliano et al., 2021). WE diets also aim to optimize both natural and human resources. Attaining Sustainable Development Goal 2 (SDG 2) necessitates coordinated efforts across the agricultural, WE nutrition, and health sectors, all promoting sustainable food systems for present and future generations, especially in the context of climate change (Berry et al., 2015). Table 5.1 summarizes various initiatives focused on leveraging desert WE plants to promote nutrition and health.

WE food systems in desert zones are currently facing a confluence of challenges, including a rapidly changing climate, increasing hunger and malnutrition, and substantial social inequities (Webb et al., 2020). However, there are also significant opportunities to transform WE food systems to produce healthy and safe food in equitable ways that foster environmental sustainability (Fanzo et al., 2022). The future well-being of billions of rural desert residents is closely linked to the transformation of WE food systems, focusing on equity, nutrition, environmental sustainability, and resilience (Calicioglu et al., 2019). Addressing three key blind spots in the understanding of rural poverty and vulnerability is essential: The limited emphasis on extreme poverty and hunger, which overlooks a broader spectrum of inequalities; insufficient recognition of the diversity within rural desert households; and a lack of understanding regarding the effects of rapid structural changes in markets, the physical environment, and the political economy. A deeper comprehension of desert areas is crucial for envisioning a new policy framework that aligns rural poverty alleviation efforts with the comprehensive transformation of WE food systems (Woodhill et al., 2022).

TABLE 5.1
Global Initiatives Related to Desert WE Plants Aimed at Promoting a Healthier Food System

Initiative Name	Objective	Key Actions	Target Group	Outcomes	Citation
Global Initiative on Edible Wild Plants	Promote the use of wild edible plants for nutrition	Documentation and promotion of traditional knowledge	Local communities, women	Increased awareness and utilization of wild edibles	Bacchetta et al. (2016)
FAO Wild Foods Programme	Enhance food security and nutrition through wild foods	Training on foraging and sustainable harvesting	Rural populations	Improved nutritional intake and food diversity	Getachew et al. (2013)
Ethnobotanical Research Initiatives	Document and preserve knowledge of wild edibles	Research on nutritional properties and culinary uses	Researchers, local gatherers	Enhanced understanding of nutritional value and uses	Rahayu et al. (2024)
UNESCO Intangible Cultural Heritage Program	Safeguard traditional practices related to wild edibles	Community workshops and educational campaigns	Indigenous communities	Preservation of cultural heritage and biodiversity	Ubertazzi (2022)
Sustainable Food Systems in Desert Regions	Foster sustainable use of natural resources	Policy development and community engagement	Policy makers, NGOs	Improved sustainability practices and local food systems	Joshi et al. (2023)

Analyzing WE food systems in arid and semi-arid countries reveals that water availability is a critical limiting factor. Many of these countries are net food importers and rely on WE food subsidy systems, as their water resources do not support national food self-sufficiency (Terwisscha van Scheltinga et al., 2021). Moreover, implementing WE food subsidy policies alongside smart water footprint strategies can create a cohesive policy framework that fosters synergies among the three key food system outcomes, facilitating the development of effective transformation pathways for food systems (Béné et al., 2019). In the evolving fields of agriculture and food science, integrating emergent WE crops presents a groundbreaking approach to diversifying agriculture. This strategy offers sustainable cultivation methods, enhances nutritional security, and creates economic opportunities in response to changing environmental and market conditions, all while positively impacting human health (Matías et al., 2024; Ouda et al., 2022). Furthermore, incorporating WE crops into crop rotation systems can disrupt cycles of pests, weeds, and diseases, enhance soil fertility, and mitigate the risk of soil degradation, thereby promoting sustainable agricultural practices. Furthermore, diversifying our agricultural systems can help reduce dependence on external food sources, which may be affected by international conflicts, as we've observed in recent times (Hellegers, 2022).

There is highly favorable substantial evidence in the literature highlighting the strong relationship between the nutrition of WE plants and human health. The nutritional quality of these plants can significantly influence human health outcomes, either positively or negatively. Nutrients from WE plants can play a vital role in sustainably enhancing agricultural production on cultivated lands, promoting soil carbon sequestration, and alleviating pressure on global peatlands (El-Ramady et al., 2022). There is growing concern regarding the role of WE medicinal plants in supporting human health and their importance for overall well-being, beyond their consumption as food (Moses &

Goossens, 2017). WE plant foods serve as a primary source of essential macro- and micro-nutrients, along with a variety of bioactive compounds that can help prevent several chronic diseases, including Alzheimer's disease, cataracts, cancer, cardiovascular disease, diabetes, and age-related functional decline (Roberts & Mattoo, 2019). The diversity of economically valuable WE and cultivated plants is a key asset for enhancing nutrition and health. While WE staples have played a vital role in supporting global food security, several challenges hinder their effective and sustainable utilization, despite their high nutritional significance. If properly accessed and utilized, plant diversity could enhance nutrition, food security, dietary variety, and health, positively impacting the livelihoods of millions in communities worldwide. WE plants represent the culmination of years of selection concerning crop varieties and desert landraces (Dulloo et al., 2014).

Approximately 821 million people worldwide experience food insecurity, with 63% residing in Asia, 31% in Africa, and 5% in Latin America and the Caribbean. Since 2014, the global number of food-insecure individuals has increased by 37 million. Climate variability and a lack of resilience to climate impacts have been identified as significant factors driving this rise (Conforti et al., 2018). Diminished yields of WE crops and rising agricultural prices exacerbate existing food insecurity, particularly for rural households that rely on food purchases and urban populations. While climate change and desertification are not the sole causes of food insecurity, they are major contributors, especially in regions heavily reliant on agriculture (Shay, 2021). WE foods offer more than just energy and nutrients; they cater to essential needs and sensory enjoyment. The consumption of WE foods is influenced by various factors, including sensory experiences and cultural beliefs. While traditionally shaped by local and seasonal availability, current consumption patterns are increasingly influenced by marketing campaigns promoting unhealthy and unsustainable food options. Both top-down and bottom-up changes are reshaping food systems, propelled by policies related to the SDGs and growing consumer awareness of environmental and health issues (Delgado et al., 2021).

5.3 WEs: SUSTAINABLE MANAGEMENT BY INDIGENOUS COMMUNITIES OF DESERTS

WE plants serve as vital resources in rural livelihoods, providing essential support for staple food supplies, enhancing food security, promoting dietary diversity, and generating sustainable income. The conservation of WE plants is crucial for ensuring household food security, fostering dietary diversity, and supporting local community incomes, while also contributing to overall biodiversity preservation (Bahru et al., 2013). WEs are an important source of essential minerals and vitamins that can help alleviate malnutrition among tribal populations living in challenging environments. These communities possess valuable knowledge about the nutritional benefits of WEs, gained through generations of experience, but this knowledge is rapidly diminishing (Aberoumand & Deokule, 2010). The information collected on WEs could be invaluable for scientists aiming to explore their nutritional profiles, processing techniques, pharmacological properties, economic potential, and breeding opportunities. Moreover, this research can support organizations focused on conserving the diverse array of WEs in this unique ecosystem. Such efforts would reduce pressure on natural resources and assist policymakers in prioritizing conservation efforts, participatory domestication, and development of suitable species (Rana et al., 2012).

The utilization of WE plants necessitates specialized cultural knowledge related to the desert ecosystems where these plants thrive. This encompasses their management in natural habitats; techniques for gathering, transporting, storing, and preparing them; and various processing methods. In this context, traditional and indigenous knowledge is crucial for the sustainability of WE resources, facilitating effective management of production systems, monitoring their status, and promoting healthier diets for future generations (Díaz-José et al., 2019). However, it is important to recognize that shifts in dietary patterns have led to significant health issues, particularly among

vulnerable populations. Therefore, biodiversity must address the needs of communities residing in regions rich in biological and cultural resources, enabling them to preserve and manage these assets to ensure access to high-quality, nutritious food (Powell et al., 2015). Gaining insight into how local communities perceive the threats and management options for WEs is crucial for formulating effective conservation strategies and action plans. Given their diverse utility, which encompasses nutritional, medicinal, construction, and cultural values, WEs face significant overexploitation due to both biotic and abiotic pressures, particularly in arid and semiarid regions. This emphasizes the urgent need for their management and conservation (Dempewolf et al., 2017; Oluoch et al., 2023).

Desert WE plants have long served as essential ecological, economic, and cultural resources for humans, particularly for indigenous peoples. Their role extends beyond direct consumption, contributing to ecosystem management services. Native WE plant species remain integral to the cultural heritage and landscapes of indigenous desert communities worldwide; they feature prominently in creation stories, traditional foods, and medicines, as well as providing habitats for spiritually significant animals. The persistence of WE desert plants in both natural and altered environments may be influenced more by their perceived value than by their empirical value. Humans tend to select and facilitate the growth of certain WE plants over others, often without fully considering their potential to support the ecosystem services upon which human communities rely (Grodsky & Hernandez, 2020). Locally desert-harvested WE plants offer both food and cash income for indigenous populations, making them crucial for global food security (Termote et al., 2011). Furthermore, WE plants significantly contribute to the productivity and stability of traditional agro-ecosystems. When managed sustainably, WE plants can serve as a viable source of income generation for rural communities (Ju et al., 2013).

WE plants supply vegetables, fruits, staple foods, and spices for indigenous communities, serving as a primary food source (Puri & Kumar, 2018). WE plants are essential for the development of new WE crops through domestication, leading to the cultivation of WE food plants and enhancing local food security and management. For many desert populations globally, the consumption of WEs has been a longstanding tradition. However, this practice has increasingly been overlooked in recent times (Thakur et al., 2020). Human societies have adapted to survive prolonged droughts, and this includes the people of the Atacama Desert, one of the driest regions on Earth (Joly et al., 2017). Our dataset offers important insights into how the use of water-efficient plants has evolved over the past 13,000 years. Those who utilized and managed WE plants demonstrated advanced understanding of their local ecosystems and established extensive networks for interaction and mobility to source plants from regions beyond their permanent habitats (Ugalde et al., 2021). Global agriculture faces increasing pressure to enhance food and feed production. While there are over 50,000 WE plant species worldwide, two-thirds of global WE supply is dominated by just three crops: wheat, maize, and rice. This heavy reliance on a limited number of commercial plant species presents nutritional, ecological, and economic risks, making it unsustainable in the long run. Incorporating a broader range of underutilized WE plants into agricultural systems could effectively address these challenges (Ramadan, 2019). Cultivating desert land poses significant challenges due to its low organic matter, reduced microbial populations, and susceptibility to various stresses such as drought and salinity. With the global population increasing, it has become crucial to develop desert soils to ensure food security through WE plants (El-Gawad & El-Shazly, 2021).

The improvement of the acceptance of ethnopharmacological knowledge data on WE plants gathered from local desert traditions should be compared, authenticated, and validated at local, regional, and global levels using diverse methodologies. In bioprospecting, priority should be given to WE plant species with well-documented traditional uses that have not yet been sufficiently explored for their potential applications in drug development (Yaseen et al., 2019). Preserving and maintaining traditional knowledge related to the conservation and sustainable use of WE biological diversity is essential for the survival of this historic desert biome. Effective long-term conservation of desert biodiversity necessitates the implementation of appropriate policies that promote both conservation efforts and the sustainable utilization of natural resources (Wariss

et al., 2021). Global trade and markets significantly influence dietary and lifestyle habits related to WEs, often leading indigenous and vulnerable communities to increase their consumption of highly processed foods with low nutritional value (Pawera et al., 2020). Key barriers to greater utilization of WEs include a lack of information, data, market infrastructure, research, and supportive policies (Heinrich et al., 2016). Furthermore, the food and agriculture sectors have largely overlooked WE species in favor of cash crops and starchy staples. Research on WEs is challenging, as documentation is often inadequate; many assessments and studies on production diversity fail to account for these plants, which are typically uncultivated and preserved within the social memory of communities (Tata Ngome et al., 2017).

5.4 WEs' DIETARY DEVELOPMENT: ECOSYSTEM CONSERVATION AND SUSTAINABILITY

It is increasingly evident that ethnopharmacology is intrinsically linked to the production of WE foods, human nutrition, and the conservation of the biodiversity that underpins these resources (Heywood, 2011). The sustainable utilization of natural and agricultural biodiversity in the WE diet can play a crucial role in preserving existing food biodiversity, combating malnutrition, and alleviating the negative impacts of dietary shifts globally (Penafiel et al., 2011). However, there is a concerning decline in biological diversity across wild and agricultural ecosystems worldwide. This trend adversely impacts livelihoods, particularly for rural communities in desert regions that rely on WE foods provided by local biodiversity (Frison et al., 2006). This situation is multifaceted, as it is essential to ensure the sustainable production of safe and nutritious WE foods while safeguarding biodiversity. This balance is crucial for maintaining the provision of other goods and ecosystem services that are vital for human well-being, both directly and indirectly. Furthermore, it is important to support societal adaptation to climate-related environmental changes that may disrupt WE food production and threaten livelihoods (Abarca-Gómez et al., 2017). Neglected and underutilized WE species, including wild, domesticated, and semi-domesticated plants, hold significant potential to enhance food security and sovereignty. However, their value remains largely unrecognized due to their limited competitiveness with commodity crops in mainstream agriculture (Tuomisto et al., 2020).

In regions such as sub-Saharan Africa and South Asia, there is a pressing need to increase the consumption of nutrient-dense WE foods to combat deficiencies in essential nutrients like folate, potassium, and vitamin A (Vos et al., 2020). Meanwhile, in North America and Europe, transitioning toward more plant-based WE diets could promote better health and simultaneously decrease per capita environmental footprints (Springmann et al., 2018). These findings can inform policymakers in developing country-specific strategies for promoting sustainable dietary practices, and they can also guide the WE food industry in providing sustainable food options tailored to regional needs (Chen et al., 2022). Consuming local WE plants also supports sustainability. The levels of health-promoting compounds can vary both among different WE species and within the same species (Åhlberg, 2021). Future research could identify which species within each ecosystem are particularly valuable for conserving sustainable sources of health-promoting compounds and essential nutrients (Cannataro et al., 2021). WEs are species that grow naturally in their habitats without cultivation or domestication, serving as accessible sources of food, medicine, and economic value for local communities. Recently, WEs have faced threats from over-exploitation, land-use changes, and biodiversity loss, primarily due to agricultural expansion. Consequently, there is a need to enhance conservation practices by implementing management strategies that prioritize species currently utilized by local communities (Suwardi & Navia, 2023). Globally, contemporary diets provide greater diversity in WE plant-based food sources. However, limited access to and affordability of these foods, such as whole grains, legumes, fruits, and vegetables, along with their associated health benefits, pose significant food and nutritional security challenges for impoverished populations (Sarkar

et al., 2020). This restricted access to healthy food options, combined with various socioeconomic burdens, including land loss, limited economic opportunities, and psychological trauma from colonization, has significantly exacerbated health disparities related to noncommunicable chronic diseases between indigenous and non-indigenous peoples (Sabaté et al., 2016).

Multidisciplinary approaches that integrate chemistry, process engineering, and sustainability science are essential for addressing transformative challenges in three interrelated areas of WE food: sustainable diets, the valorization of unavoidable food supply chain waste, and the circularity of food value chain systems, all aligned with the United Nations' 17 SDGs (Sadhukhan et al., 2019). In the realm of sustainable diets, comprehensive life cycle assessments utilizing global life cycle inventory datasets and recommended daily servings are conducted to evaluate and rank WE food options. This assessment encompasses all food groups from fresh fruits and vegetables to lentils, pulses, grains, and livestock, focusing on health and environmental impacts to highlight the importance of a plant-based WE diet, particularly in terms of plant-based protein sources, for achieving holistic sustainability and stability of the Earth's systems (Roe et al., 2019). Regarding unavoidable food supply chain waste, economically viable and synergistically integrated innovative biorefinery systems are proposed to convert unavoidable food waste into functional chemicals and energy vectors (Sadhukhan et al., 2020). Feeding the global population relies on safeguarding our vital ecosystems and biodiversity. Growing public awareness of the challenges associated with the industrialized (Çakmakçı et al., 2023) Western food system has led to greater support for innovative markets focused on sustainable food production that is economically viable, socially equitable, and ecologically sound. This shift has also intensified calls for changes in agricultural policies and regulations (Allen & Prosperi, 2016).

Intensive management practices in WE agro-food enterprises, along with the overuse of inputs, may threaten the conservation of terrestrial ecosystems and significantly impact biodiversity (Mattas et al., 2023). Conversely, the production of plant-based foods in the West generates lower greenhouse gas emissions compared to animal-based foods, indicating that a transition to plant-based diets could contribute to the preservation of biodiversity (Sala et al., 2017). The connection between food and the environment is clear, particularly in relation to nutrition and sustainable healthy WE diets. Achieving this requires systemic change and research into new foods, specifically novel proteins such as plant-based alternatives and their biological and chemical modifications (Varzakas & Smaoui, 2024). The European Commission prioritizes the development of resilient sustainable food systems that emphasize health and inclusivity. Key initiatives like the Farm to Fork strategy and the European Green Deal are vital for the success of these food systems. Moreover, Food 2030, an EU framework for research and innovation, facilitates the transition to sustainable, innovative, and holistic food systems that operate within planetary boundaries (Kuc-Czarnecka et al., 2023). A significant portion of the existential threat posed by climate change stems from current human dietary patterns (Carey et al., 2023). In the past decade, research assessing the environmental impacts of plant-based WE diets has increased, and a comprehensive synthesis of this data is now warranted. Moreover, adopting a fully plant-based WE diet could substantially reduce global water consumption and land use compared to an omnivorous diet (Rogelj et al., 2018). Patterns of WE plant diversity, when used as traditional food components, highlight their potential as natural resources. Within the realm of cultural ecosystem services, findings indicate that WE plants serve as a catalyst for enhancing local eco-gastro tourism, offering a rich array of experiences through authentic gastronomy, herbal tours, and the promotion of rare species (Lukovic et al., 2023).

WE dietary diversity is a recognized public health principle, and measuring it is crucial for assessing diet quality and food security. However, traditional scoring methods that compare food groups do not adequately reflect the nutritional variability and ecosystem services provided by dietary richness and diversity within these groups (Hanley-Cook et al., 2023). They also overlook the relative distribution evenness and moderation of WE species or varieties across entire diets. The composition of global WE food supplies and diets has become increasingly homogeneous, with a

diminishing number of WE species. The variation in food supplies between countries has decreased by approximately 70% over the past 50 years (Dale et al., 2017). The advancement of sustainable WE diets for nutrition security and sustainable development requires well-defined nutrition metrics to evaluate dietary nutritional quality (Dave et al., 2023). Key metrics commonly utilized in the assessment of sustainable diets include food composition, nutrient requirements, and dietary intake (Afshin et al., 2019). Local WE food crops encompass numerous orphan or minor species that are either indigenous or naturalized, as well as WE plants that have likely co-evolved with hunter-gatherer and forager societies since the Stone Age. It is essential to promote the adoption and expansion of these crops, conduct regular evaluations, and implement breeding programs for improved varieties. Moreover, sustainable policies, production practices, and marketing strategies for local WE food crops must be developed and supported (Ogwu, 2023). The current WE food system highlights an urgent need for a transition toward sustainability, as food insecurity, malnutrition, and obesity impact over half of the global population due to the consumption of contaminated foods, including those with endocrine disruptors that can have serious health consequences (Araújo et al., 2023). Looking ahead, it is crucial to prioritize insights into nanotechnological processing for the development of nano-fortified WE functional foods and nutraceuticals to address the challenges of food scarcity. In the 21st-century food sector, in alignment with the SDGs, nanotech-based WE food processing represents a new frontier that significantly enhances food quality, nutritional value, safety, and the development of nano-fortified functional foods (Aguilar-Pérez et al., 2023; Bombelli et al., 2019).

5.5 UNLOCKING DESERT WE RESOURCES TO PROMOTE SUSTAINABLE AGRICULTURE

Agricultural advancements often encounter challenges in identifying the optimal cropping patterns needed to achieve specific objectives, such as maximizing profit, minimizing costs, or increasing production. Optimization techniques are employed to ascertain the most effective solutions for these issues, particularly in relation to the production of WE food plants, while adhering to defined constraints (Moghazy & Kaluarachchi, 2020). While arid environmental conditions globally pose significant challenges to the sustainability of living organisms, certain WE plant species possess unique genotypic, biochemical, and physiological adaptations that enable them to thrive under such harsh circumstances (Mohanta et al., 2024). Considerable efforts have been made to utilize arid land for sustainable agriculture; however, extreme environmental conditions continue to hinder agricultural production. Nonetheless, researchers are actively engaged in developing new crop varieties capable of withstanding arid environments to promote sustainable agricultural practices (Carvajal et al., 2017). Agricultural production has been enhanced with limited resources, and significant technological advancements have been introduced throughout human history (Ayaz et al., 2019). However, the interplay between a growing population and climate change continually threatens the balance of supply and demand for WE foods. Given the ongoing rise in the global population, it is imperative to pay closer attention to the nutritional value and quality of WE foods. To meet future food demands, food production must be doubled by 2050 (Khan et al., 2021).

Diversifying crops and varieties, along with reducing tillage and other field practices through the development and introduction of herbaceous perennial crops, is proposed as a regenerative WE food system. This approach aims to enhance carbon sequestration, provide economic benefits for growers, and deliver social and environmental advantages (Pathirana & Carimi, 2022). Sustainable management of agroecosystems is also crucial for achieving WE food and nutritional security for current and future generations, as the quality of human life, health, and well-being is directly linked to the accessibility, affordability, and availability of healthy and nutritious WE foods (Dubey et al., 2021; Woolston, 2020). Today's population is depleting natural resources, jeopardizing future generations' access to nutritious WE foods and clean air (Umesha et al., 2018). Sustainable agricultural

approaches and practices offer solutions for producing WE foods and other agricultural products with minimal environmental impact, ensuring that food accessibility and availability are maintained without compromising the well-being of future generations (Muhie, 2022). The growth of the global population, coupled with climate change and rising levels of hidden hunger, emphasizes the urgent need for sustainable and eco-friendly agricultural practices aimed at enhancing the yield and nutritional value of WE crops (Roriz et al., 2020). It is crucial to implement sustainable strategies to address these pressing societal challenges and ensure the production of WE foods that are both nutritionally rich and environmentally sustainable (Nath et al., 2017). Sustainable agriculture is essential for addressing the increasing demand for WE foods in the global population. The rising need for safe and nutritious food, along with the ongoing ecological degradation linked to conventional agricultural practices, presents significant global challenges (Safdar et al., 2022).

Modern agriculture must be adapted to the impacts of climate change and the rising demand for WE foods driven by population growth. Given the limitations of natural resources, sustainable cropping practices are crucial, particularly for horticultural crops, which are more vulnerable to climate extremes and require higher agricultural inputs (Shahrajabian et al., 2021). The role of nano-nutrients is essential for assessing the effects and potential risks of nanomaterials within the food production chain (Ghosh & Bera, 2021). Sustainable and precision farming practices are critical for fulfilling the growing global demand for WE foods while minimizing negative impacts on the environment, including soil, air, and water quality. To adequately feed the increasing global population, it is necessary to boost WE food production proportionately (Faizan et al., 2024). The numerous challenges currently facing agriculture could lead to significant declines in global food production and distribution. Innovative approaches, such as nanofertilizers, hold significant potential for enhancing WE food production, improving food quality, and reducing waste (Tyagi et al., 2022). In conventional farming, nearly one third of WE crops are lost, primarily due to pest infestations, microbial attacks, natural disasters, poor soil quality, and insufficient nutrient availability. There is an urgent need for innovative technologies to address these challenges (Mittal et al., 2020). In this context, nanotechnology has played a pivotal role in the agrotechnological revolution, with the potential to transform resilient agricultural systems and enhance food security. Undoubtedly, nanotechnology is integral to various aspects of the food industry (Leso et al., 2019). In recent years, the importance of conserving agricultural heritage systems (AHSs) in sustainable agriculture has gained global recognition (Liu et al., 2024). AHSs not only preserve agricultural biodiversity and encapsulate a wealth of indigenous knowledge, but they also offer a variety of products and services that support local livelihoods and WE food security, thereby enhancing overall quality of life (Zhang et al., 2024). Nanotechnology and its applications have emerged as a pioneering and promising approach for transforming conventional WE food and agricultural industries, aimed at achieving sustainable farming and enhancing food security, quality, and safety (Ashraf et al., 2021). Recent advancements in nanotechnology are paving new pathways and driving significant changes in how WE food is perceived across various stages, including farming, transportation, processing, packaging, storage, monitoring, and consumption (Mansoori, 2017).

Intensive conventional farming and climate change have caused significant ecological harm and jeopardized global food security, necessitating a shift in agricultural management and public policies towards a more sustainable development model (Ur Rahim et al., 2021). The projected increase in the global population to 9.7 billion by 2050 is driving higher demand for protein in human diets. Green WE leaves from various food plants offer a cost-effective, plentiful, and sustainable source of protein suitable for human consumption (Hadidi et al., 2023). Rural-to-urban migration is driving increased demand for WE foods and is linked to a greater risk of farmers losing their land to urbanization, resulting in a reduction of cultivated land (Lombardi et al., 2021). The challenge for agriculture is to provide for a growing population while contending with limited and degraded agricultural land. Traditionally, agricultural intensification has been regarded as the primary strategy to achieve global food security goals (Paz et al., 2020). Malnutrition, which includes undernutrition, micronutrient deficiencies, and overnutrition, is more prevalent than hunger alone and impacts

most countries worldwide (Ebert, 2020). The diversity and quality of WE foods produced and consumed are critical factors in addressing the triple burden of malnutrition. Global demand for WE agricultural crops is expected to rise by 2050, driven by population growth, increased per capita purchasing power leading to higher consumption of meat and dairy, and the use of biofuels (Valin et al., 2014). Agronomy encompasses the science and technology of managing crops and soils for the production of WE foods, fiber, feed, and fuel. As the global population increases, agronomy will become increasingly essential in addressing rising demands for WE foods while preserving natural resources (Saxena et al., 2024). Ongoing innovation and the dissemination of agronomic knowledge are vital for feeding growing populations while safeguarding environmental quality. Collaborative efforts among researchers, educators, policymakers, and farmers will be crucial to implement advanced, context-specific agronomic solutions that ensure agricultural sustainability in the future (Mohanty et al., 2024).

5.6 PROMOTING WEs IN THE DESERT: FUTURE IMPLICATIONS TOWARDS THE SUSTAINABLE VALUE CHAIN

Globally, a variety of plants are consumed as grains, vegetables, and WE fruits, yet only a few have been developed as commercial cash crops. Numerous neglected, underutilized, or orphan WE plant species remain unexplored, offering potential to diversify human diets and enhance food production, thereby promoting more sustainable and resilient agro- and horticultural WE food systems (Chlachula, 2021). Historically, sustainable agriculture was easier to implement when human populations and reliance on chemicals (fertilizers and pesticides) were lower. The primary WE crops that have been the focus of agricultural domestication include wheat, rice, corn, and potatoes. The Green Revolution's further intensification of food production significantly addressed nutritional needs. However, the overuse of antimicrobial agents, toxic chemicals, and pesticides has led to declines in biodiversity and human health. Moreover, climate change is increasingly impacting WE crop production in key growing regions, resulting in rising prices (Baldermann et al., 2016). Scaling up the value chains of indigenous WE species has improved the livelihoods and resilience of smallholder farmers to climate change by: (1) developing sustainable plant propagation techniques for leaf and fruit production within farm fields, thereby increasing access to these nutritious plants while alleviating pressure on wild populations and conserving biodiversity; and (2) enhancing processing methods for food derived from various plant parts to ensure the availability of micronutrients (Assogbadjo et al., 2023). Promoting value chains of multipurpose indigenous WE species that are well-suited to local conditions is essential for enhancing the livelihoods and resilience of smallholder farmers to climate change, particularly in semi-arid and arid desert regions (Fandohan, 2016).

In the coming decades, meeting the nutritional needs of a growing global population sustainably will necessitate significant enhancements to the global food system. The primary challenge will be to increase the production of WE foods while using the same or fewer resources and minimizing waste. Food security encompasses four key dimensions: availability, access, utilization and quality, and stability (Devaux et al., 2021). Meeting the nutritional needs of a growing population sustainably will demand significant advancements in the global food system, which must support farmers' livelihoods while delivering nutritious products to consumers and reducing the current environmental impact. A key challenge is to enhance the production of WE foods using the same or fewer resources, without exacerbating inequality or causing detrimental environmental effects (Wu et al., 2018). The future of agricultural sustainability lies in developing a resilient and sustainable farming system. There are four identified types of uncertainty related to WE crops: product, process, market, and environment, with management being the central challenge (Lezoche et al., 2020). Ineffective management of these uncertainties adversely affects product safety, quality, quantity, and waste, as well as the utilization of human, technological, and natural resources. In today's

world and increasingly in the future, data serves as the essential foundation for any business, and agriculture is no exception, but rather a leading example (Mondino & Gonzalez-Andujar, 2019). The global value chain, frequently equated with the global supply chain, encompasses the entities and activities involved in the production and distribution of goods and services across various regions, aimed at delivering enhanced customer value (Ali et al., 2022). The disruptions triggered by the COVID-19 pandemic have highlighted vulnerabilities, preparedness gaps, and missing links within today's extensive and globally interconnected value chains. The WE food agriculture sector and its associated value chains were particularly affected, especially with the implementation of domestic and international travel restrictions (Ali & Gurd, 2020).

The current agricultural food supply chain faces several challenges related to the increasing demand for WE food items and consumer preferences concerning food safety. Alongside growing sustainability concerns, stringent government regulations, food security issues, and traceability requirements compel managers, industries, and practitioners within the agricultural food supply chain to adopt new tools, techniques, and methodologies for modeling existing supply chain challenges and designing corresponding food logistics networks (Yadav et al., 2022). Many of the agricultural food supply issues can be addressed through the efficient design of a WE food logistics network, which includes optimizing the locations of supply chain nodes, making more sustainable choices throughout the food distribution process, improving distribution routes, and restructuring the WE food logistics chain network (Paciarotti & Torregiani, 2021). Circular WE food supply chains have the potential to create value-added food products. However, introducing new loops in these supply chains may also introduce new risks. The primary challenges include the potential for WE food contamination and loss of traceability due to batch dispersion (Lambrechts, 2020). Therefore, a comprehensive research approach is essential to integrate value addition strategies with risk analysis, as well as to apply forecasting and optimization techniques across the entire supply chain. Furthermore, the management system for a WE circular supply chain should be designed and implemented at a level that transcends individual companies, involving all trading partners to ensure high transparency, interconnectivity, and overall effectiveness (Lavelli, 2021; Schanes et al., 2018). The anticipated growth in the global population, along with the corresponding rise in demand for WE foods, necessitates increased focus and attention on underutilized crop species. WE species hold significant potential to enhance food security and foster sustainable rural development and growth (Aderibigbe et al., 2022).

An ongoing debate exists regarding the optimal strategies for feeding the expanding global population over the long term and the implications for research and development. Some advocate for a new Green Revolution to ensure a stable supply of WE staple foods, while others highlight the necessity of diversifying and enhancing dietary options (Grote et al., 2021). Achieving improved food security will rely on the sustainable management and use of resources, including land, water, and nutrients, while operating within planetary boundaries. Striking the right balance between WE food production, nutritional security, environmental protection, and climate change mitigation remains a significant challenge for sustainable food systems and the effective management of land and water resources (Willett et al., 2019). As countries progress in their development, agriculture's role as a domestic employer diminishes. However, the overall WE agri-food system continues to expand, shifting the potential for agriculture-related job creation beyond the farm (Swinnen, 2018). There is a growing focus on related upstream and downstream activities, including input supply, WE food logistics, processing, retail, and food services, all of which, in conjunction with agriculture, constitute the broader agri-food system (Christiaensen et al., 2021). In recent decades, various global and domestic factors have contributed to significant and unpredictable changes in the functioning and structure of WE agri-food markets worldwide (Borsellino et al., 2020). Given the unsustainability of current patterns in WE agri-food production, processing, distribution, and consumption, along with insufficient governance of the entire food system, transitioning to sustainable agriculture and food systems is essential. This transition is crucial for effectively managing a global agri-food market capable of supporting projected population growth and ensuring universal

access to sufficient, safe, and nutritious WE food for all (Searchinger et al., 2014). Sustainability plays a crucial role in the operations of a company, particularly within the food sector, and is vital for its financial performance. Environmental concerns, along with potential economic benefits from adopting sustainable practices, necessitate the use of various tools designed for green WE supply chains. Additionally, social issues emerge, highlighting the social responsibility of food companies, which can be demonstrated through the provision of fresh products that adhere to consumption safety standards (Adekomaya et al., 2016). Perishable WE food products experience continuous deterioration and have defined expiration dates. When they arrive at retail stores, their average quality is assessed based on the remaining time they can be stored at the appropriate temperature and the remaining time available for sale. Product freshness is quantified in terms of time units (Soto-Silva et al., 2016).

The globalization of the food industry adds complexity and challenges to improving efficiency and addressing issues within WE food supply chains. Blockchain technology offers a promising decentralized solution that could enhance WE food supply chains by lowering transaction costs and time; increasing process transparency, security, and efficiency; and fostering trust among stakeholders (Li et al., 2023). WEs play a critical role in addressing nutritional deficiencies during food shortages, and their medicinal properties provide a cost-effective alternative to modern pharmaceuticals, especially in remote areas with limited healthcare access. Promoting the conservation and sustainable utilization of these plants can strengthen traditional medicine systems (Ayessou et al., 2014; Sharma & Wagh, 2024). The food industry, acknowledged by many of the SDGs, plays a vital role in supplying WE food and beverage products. Food crises lead to inconsistent access to adequate quality and quantity of food and nutrition, which is recognized as a significant global risk for society (Driessen & Heutinck, 2015; Duong et al., 2020). The achievement of many SDGs is critically dependent on the food chain at both global and local levels. Strategies for improving health through better diets include addressing hidden hunger and providing affordable WE foods for the underprivileged, as well as leveraging advanced digital technologies like machine learning and artificial intelligence (Lillford & Hermansson, 2021). While there is a global need for ongoing investment in food science and technology, their implementation will require tailored approaches in local desert regions (Knorr et al., 2018). It is essential to enhance continuous education and training through investments from both the public and private sectors. Engaging consumers to raise their awareness of new technologies and their benefits to WE food supply and healthier diets is also crucial (Gibney, 2019).

The value chain for WE food production and processing is facing significant pressures from various sources. There is a rising demand fueled by a growing and wealthier population, while simultaneously, resources are diminishing due to urbanization, land degradation, pollution, and competition from alternative agricultural practices, such as biofuel production (Connor & Mínguez, 2012). Additionally, both consumers and regulators are imposing stricter requirements on production methods, emphasizing the need for higher quality, reduced chemical usage, and environmentally sustainable practices throughout the entire food supply chain (Berman et al., 2013). Addressing these challenges necessitates the development of efficient and sustainable agricultural practices that are aligned across the value chain, enabling the use of renewable resources without compromising environmental integrity (Albajes et al., 2013). Consequently, agricultural and horticultural research must focus on developing strategies that not only increase food production but also enhance access to more nutritious WE foods (Aworh, 2015). One effective approach is to promote dietary biodiversity among local populations. Creating products that resonate with local preferences can improve the consumption of nutritious WE foods and enhance nutritional access. It is essential to recognize that dietary patterns vary globally, necessitating that recommendations for food selection and preparation align with the eating and cooking habits of the local communities (Baldermann et al., 2016). The Farm to Fork Strategy emphasizes that research and innovation are crucial for speeding up the shift toward sustainable, healthy, and inclusive WE food systems, encompassing all stages from production to consumption (Riccaboni et al., 2021).

The body of literature in agriculture and food science focusing on waste-to-value applications for upcycling by-product WE ingredients is growing. However, this research often overlooks an international trade and sustainability systems perspective (Reardon & Minten, 2021). Implementing a waste-to-value approach in the export of underutilized WEs can enhance local employment, conserve natural resources, facilitate the beneficial use of side streams in local energy production, promote eco-friendly packaging for transport, and add health benefits to consumer products. Nevertheless, challenges must be addressed to ensure that these environmental and social advantages are realized (Aschemann-Witzel et al., 2023). The preservation and promotion of WE food heritage are frequently viewed as viable strategies for attaining social and cultural sustainability goals (Barrionuevo et al., 2019). The close interdependence between intangible and tangible aspects during the heritagization of WE foods is examined, along with how local and global interactions can influence and shape this process. This topic has been central to discussions in WE food and social sciences, particularly concerning the relationship between promoting local agri-food resources, rural development, and desert food tourism (Fusté-Forné, 2020; Zocchi et al., 2021).

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